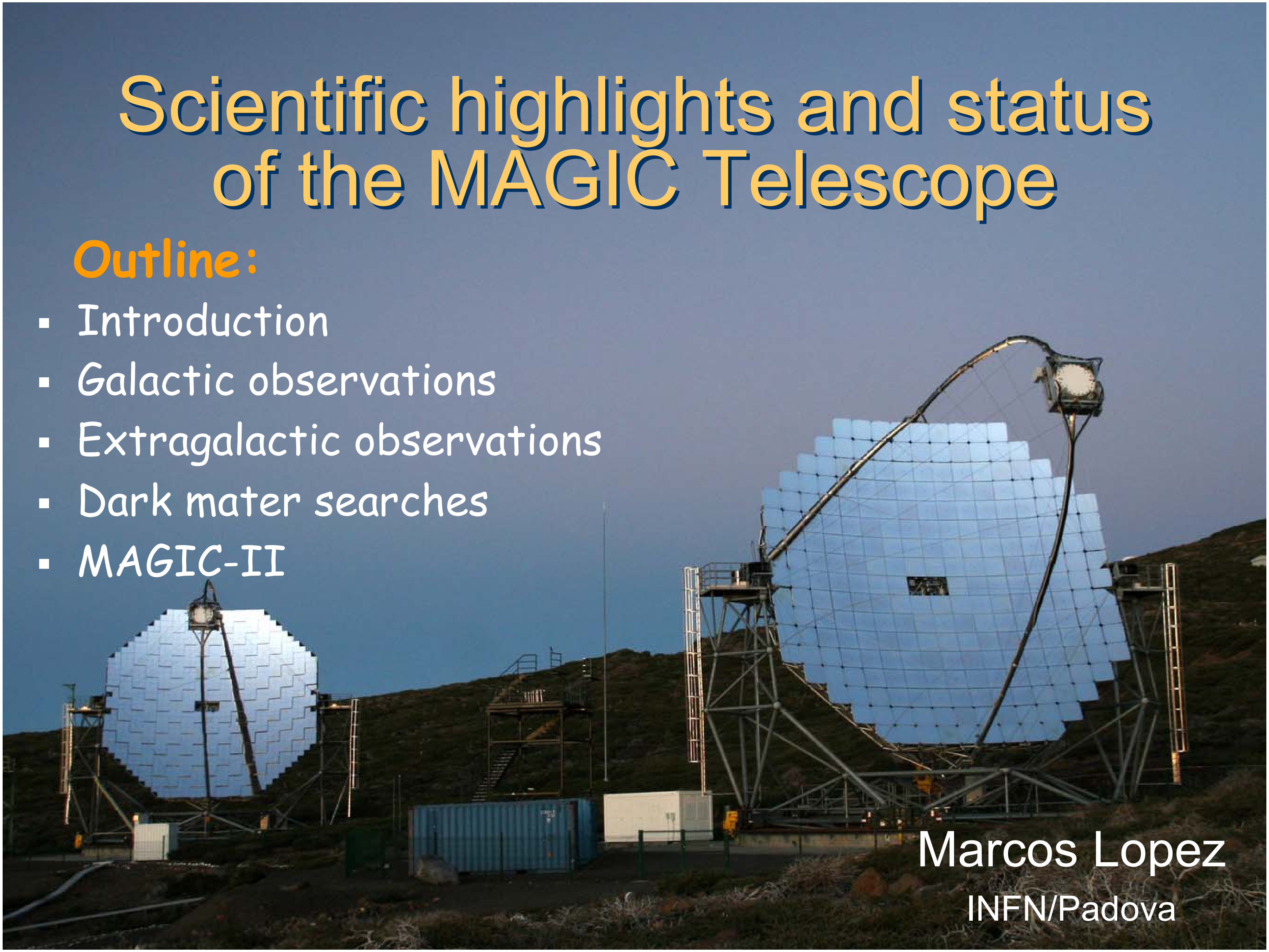
Scientific highlights and status of the MAGIC Telescope

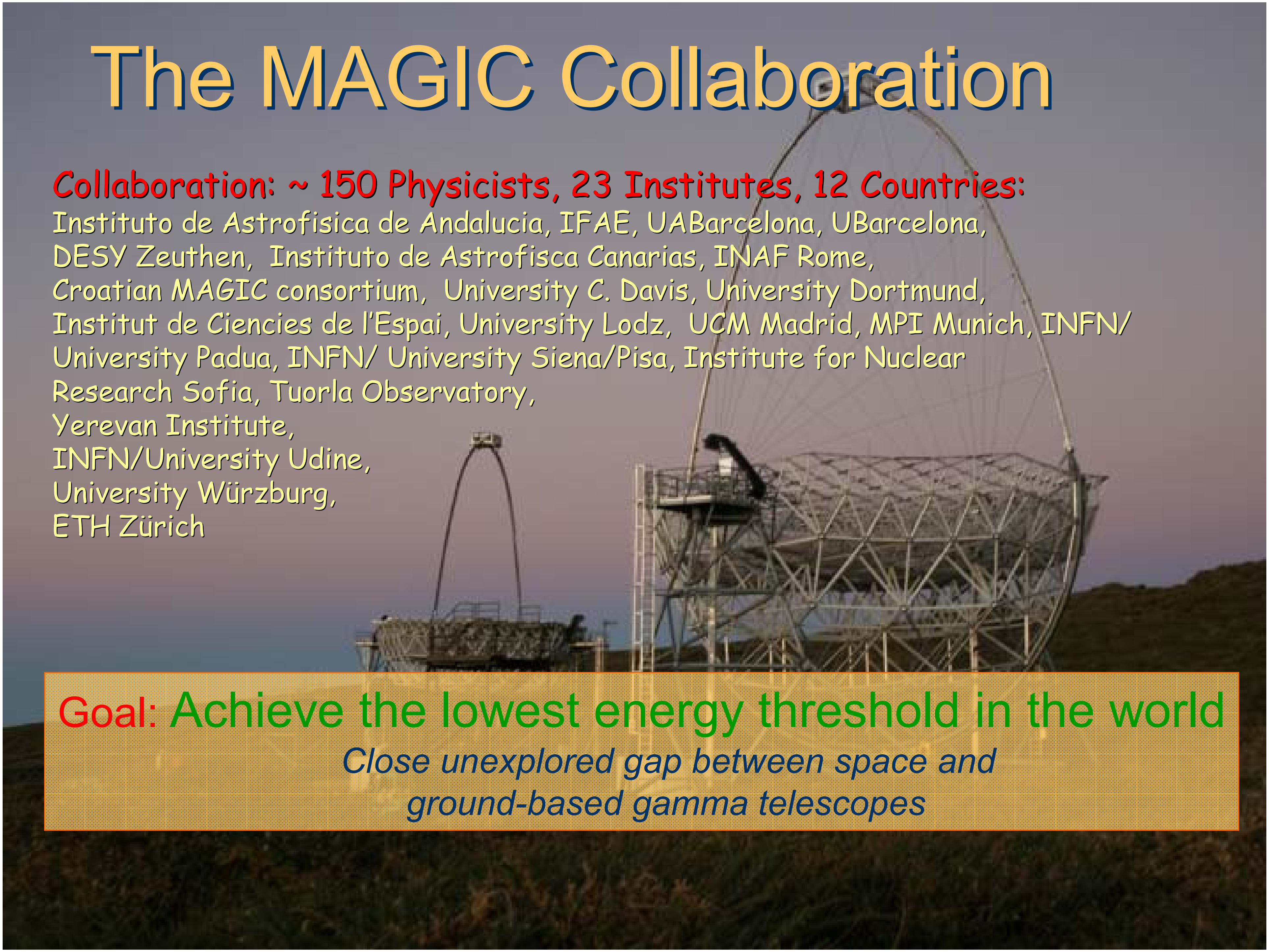
Outline:

- Introduction
- Galactic observations
- Extragalactic observations
- Dark mater searches
- MAGIC-II



Marcos Lopez
INFN/Padova

The MAGIC Collaboration



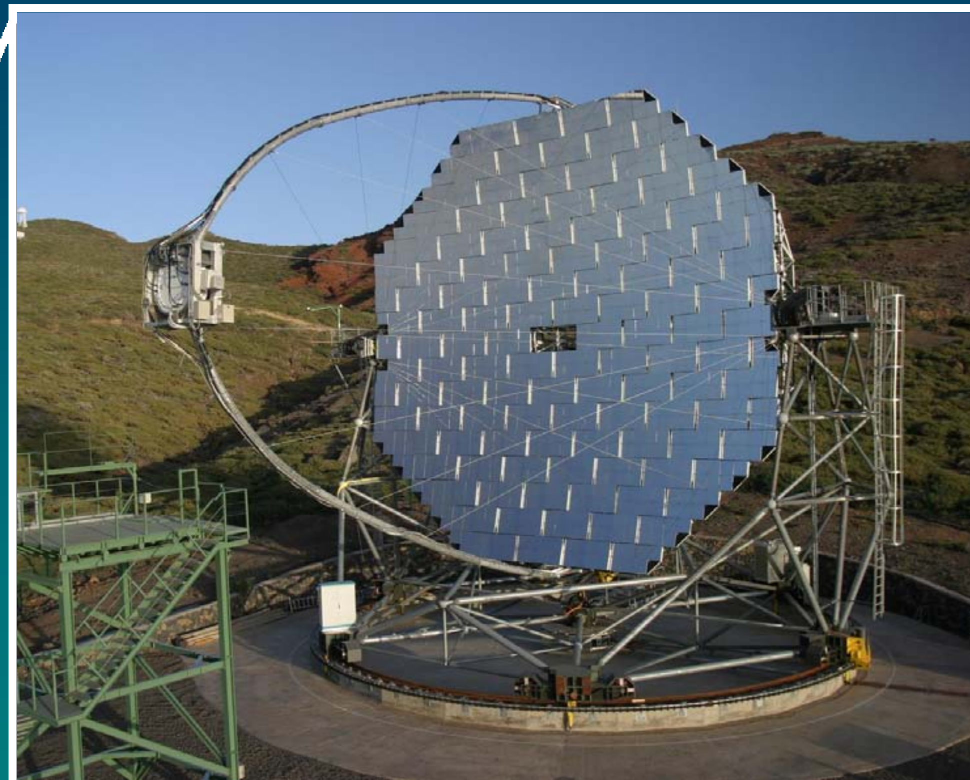
Collaboration: ~ 150 Physicists, 23 Institutes, 12 Countries:

Instituto de Astrofisica de Andalucia, IFAE, UABarcelona, UBarcelona, DESY Zeuthen, Instituto de Astrofisca Canarias, INAF Rome, Croatian MAGIC consortium, University C. Davis, University Dortmund, Institut de Ciencies de l'Espai, University Lodz, UCM Madrid, MPI Munich, INFN/ University Padua, INFN/ University Siena/Pisa, Institute for Nuclear Research Sofia, Tuorla Observatory,
Yerevan Institute,
INFN/University Udine,
University Würzburg,
ETH Zürich

Goal: Achieve the lowest energy threshold in the world

Close unexplored gap between space and ground-based gamma telescopes

The MAGIC telescope

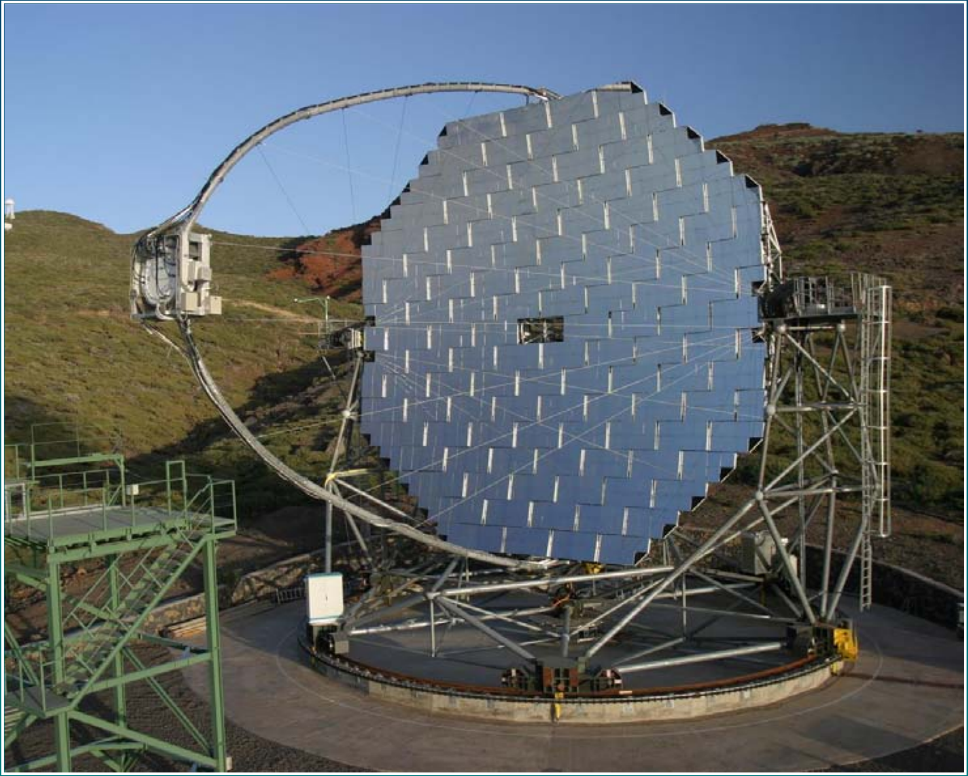


The MAGIC telescope

MAGIC

- Largest single dish CT:
  17 m Ø mirror dish (241 m^2)
- Camera with 577 enhanced QE PMT's, 3.5° FoV
- Ultra-light carbon fibre frame:
  - Fast repositioning for GRBs: average < 40 s
- Enhanced duty cycle (by 50%) thanks to moonlight & twilight observations
- Performance:
  - Low energy threshold:
    - Std: 55 GeV
    - Sumtrigger: 25 GeV
  - Sensitivity: 1.6% Crab/50h
  - Angular resolution: ~ 0.1°
  - Energy resolution: 20-30%

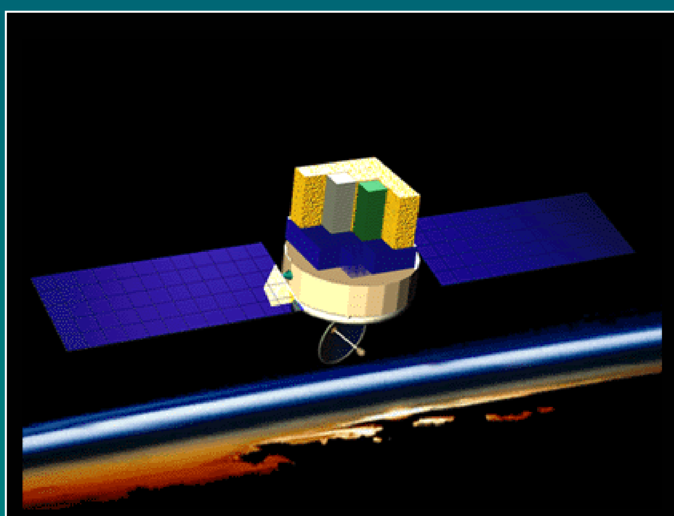
In regular observation mode since fall 2004



Basic fact: γ-rays absorbed in atmosphere

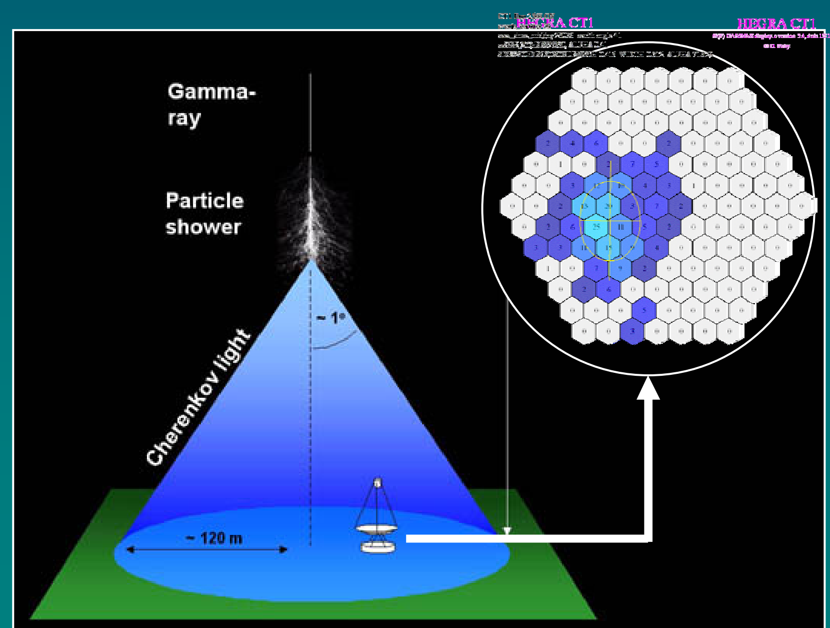
Satellites

- **Direct detection**
- Small background
- Small Effective Area ~1m^2



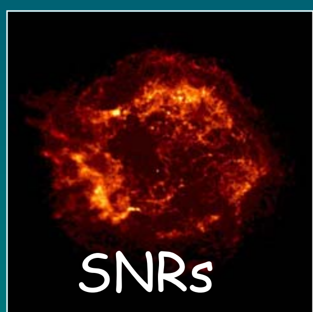
Ground Detectors

- **Indirect detection**
- Huge Effective Area ~ 10^{5}m^2
- Enormous hadronic background

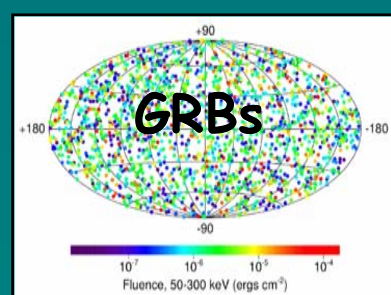


MAGIC Physics Targets

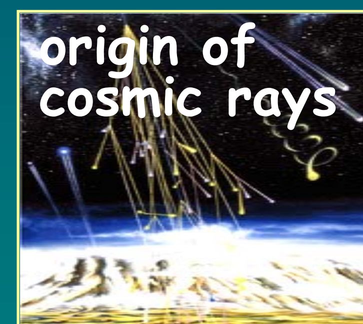
Galactic

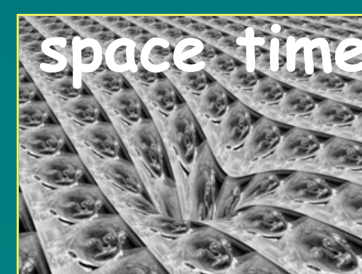


Extragalactic



Fundamental Physics

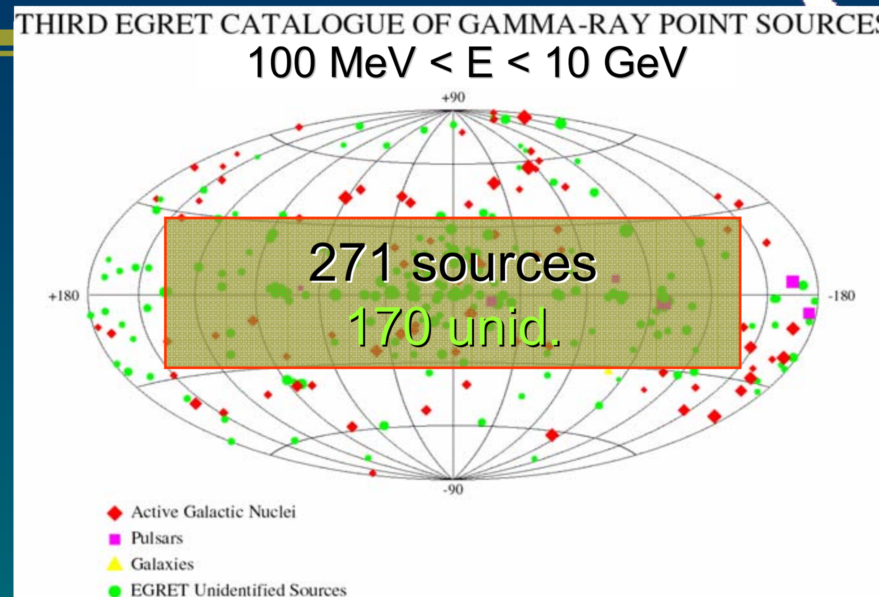


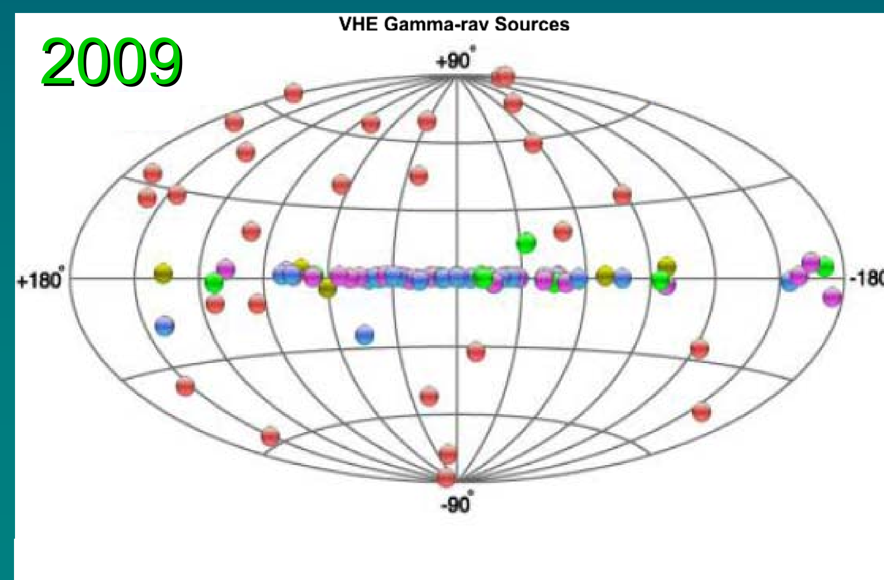


The γ–ray sky

MAGIC

- EGRET gave a nice crowded picture of energies up to 10 GeV.
- Ground-based experiments show very few sources In spite of having much better sensitivity!
- Situation dramatically changed thanks to the new generation of CTs

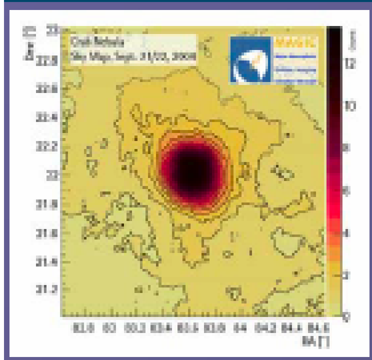




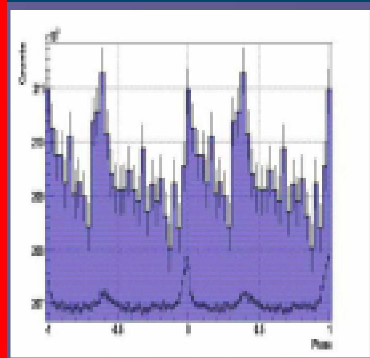
Highlights in MAGIC galactic observations

MAGIC

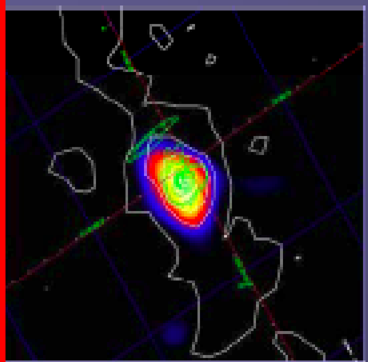
4 discoveries, 6 more detected, U.L on many others



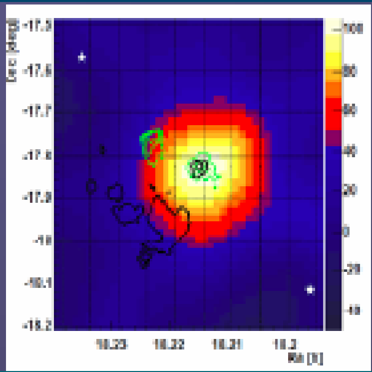
Crab Nebula



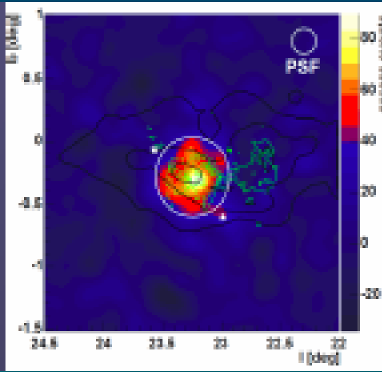
Discovery after 20years of effort



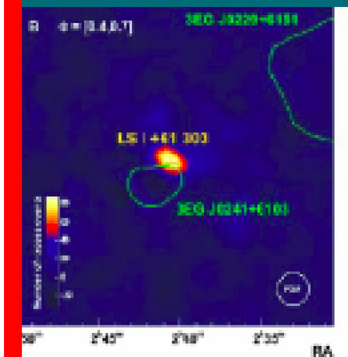
Galactic Center



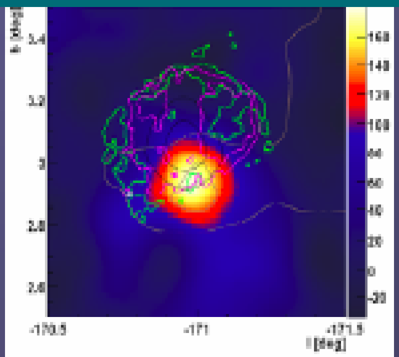
HESS J1813



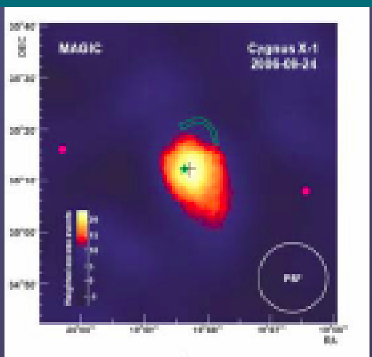
HESS J1834



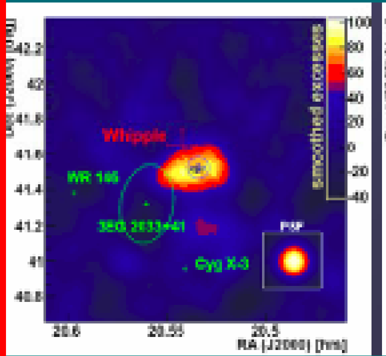
LSI+61 303



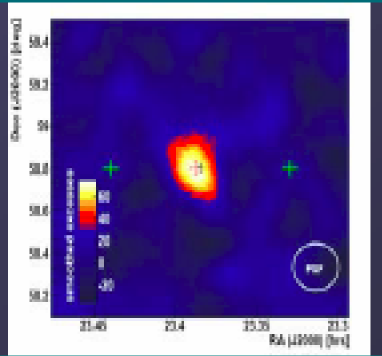
IC443



Cyg X-1



TeV 2032



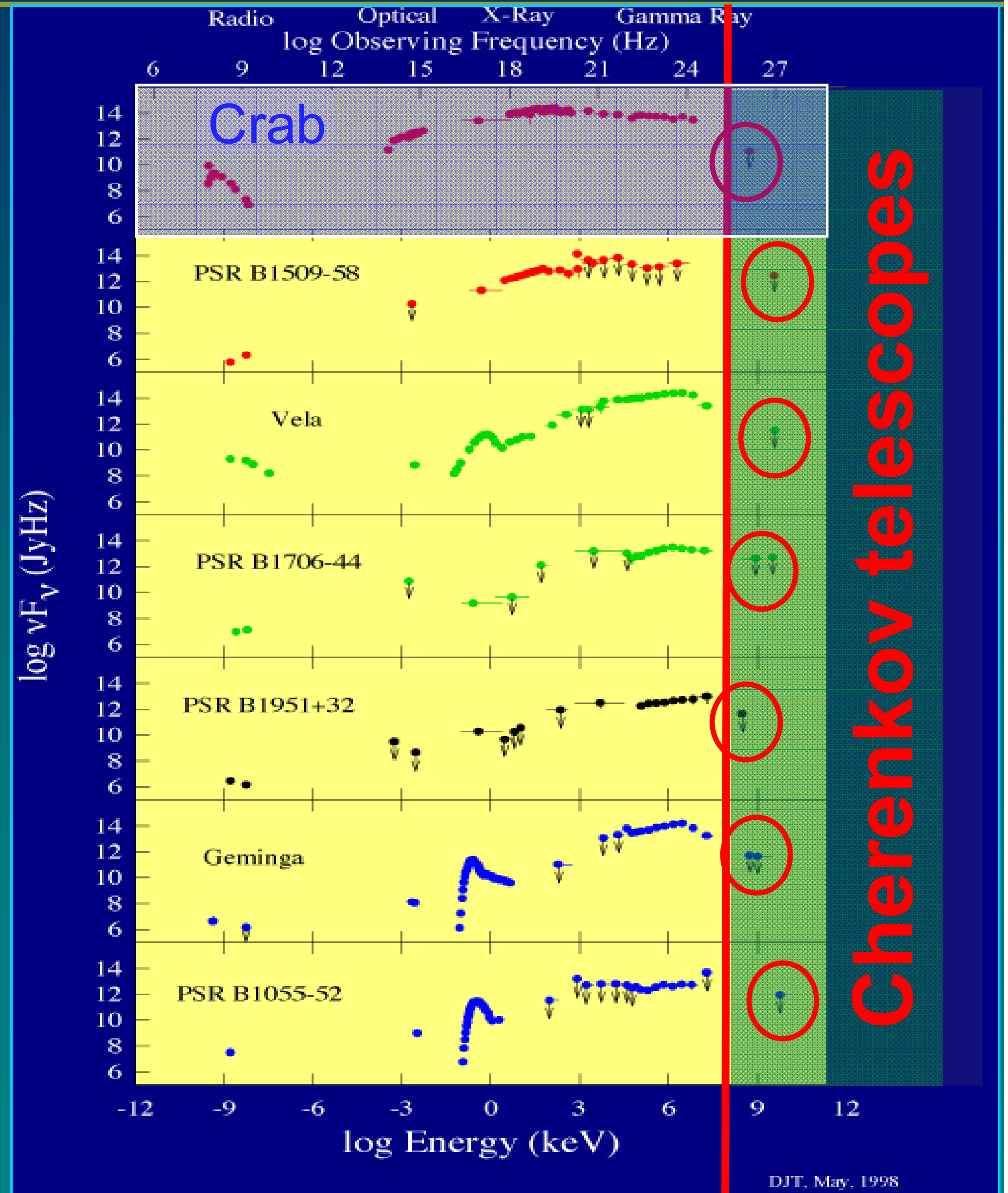
Cas-A

Pulsars visible in VHE Υ-rays?

- Maximum of emission at hard X- and γ-ray
- Spectra are very different above 1 GeV

  High energy spectral cutoffs

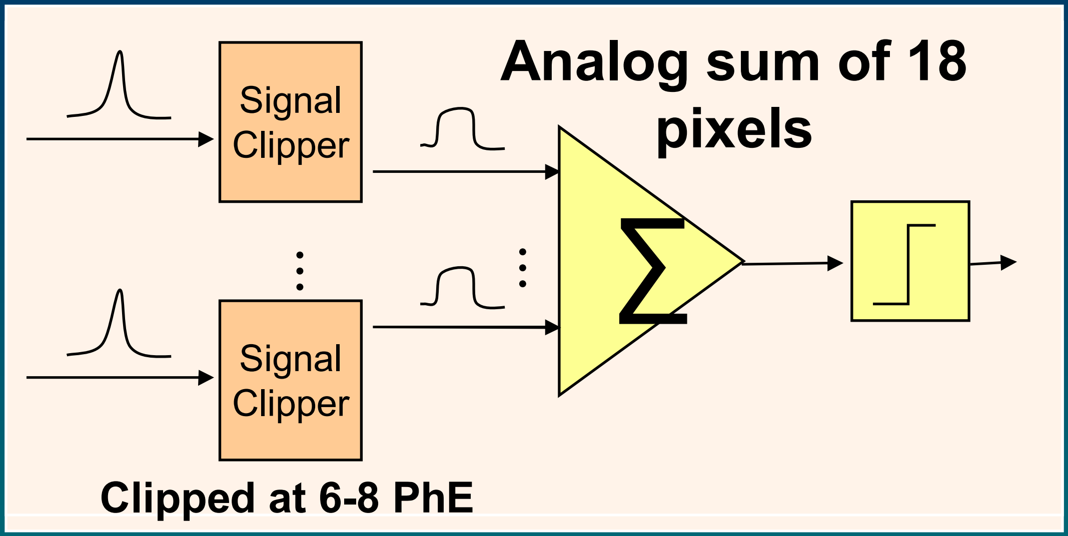
- Observational challenge since 20 years
- Instrument with sensitivity well below 100 GeV needed

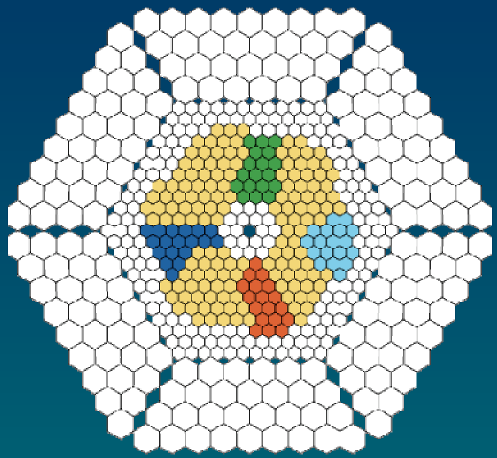


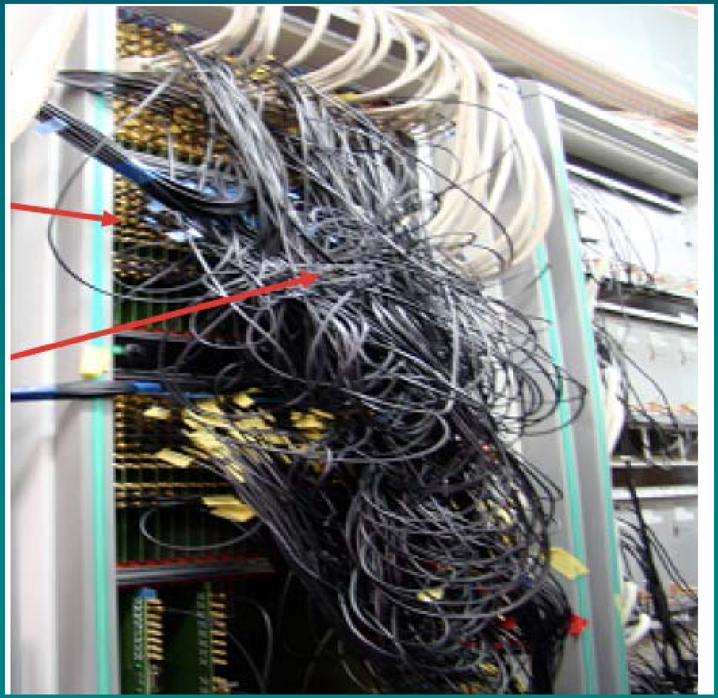
Scineghe 09, Assisi

MAGIC

A new trigger concept







MAGIC SumTrigger

- 24 Clusters of 18 pixels in a ring area
- *Add analog signals from a cluster &* discriminate on summed signal
- Problem: Large amplitude from Afterpulses
  - Solved by clipping signal
- Built in summer 2007

A new trigger concept

Pulsars

MAGIC

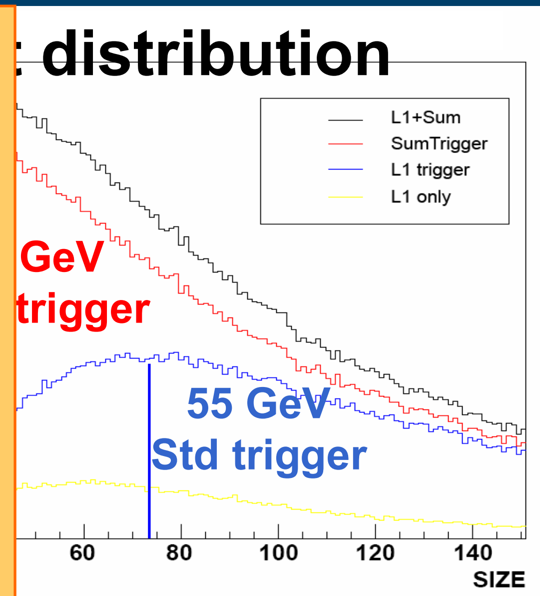
Improvements

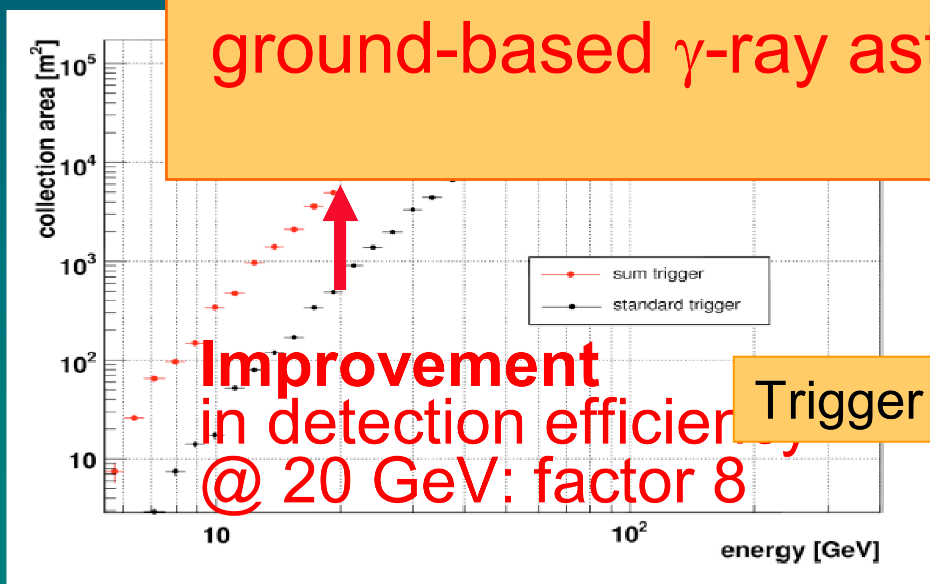
- Size
  lowe
- High
- Sum

in pa

Low trigger threshold
of 25 GeV:

a break-through for
ground-based γ-ray astronomy





Trigger threshold decreased in a factor ~2

Detection of the Crab pulsar above 25 GeV

Pulsars

MAGIC

Observations with new trigger

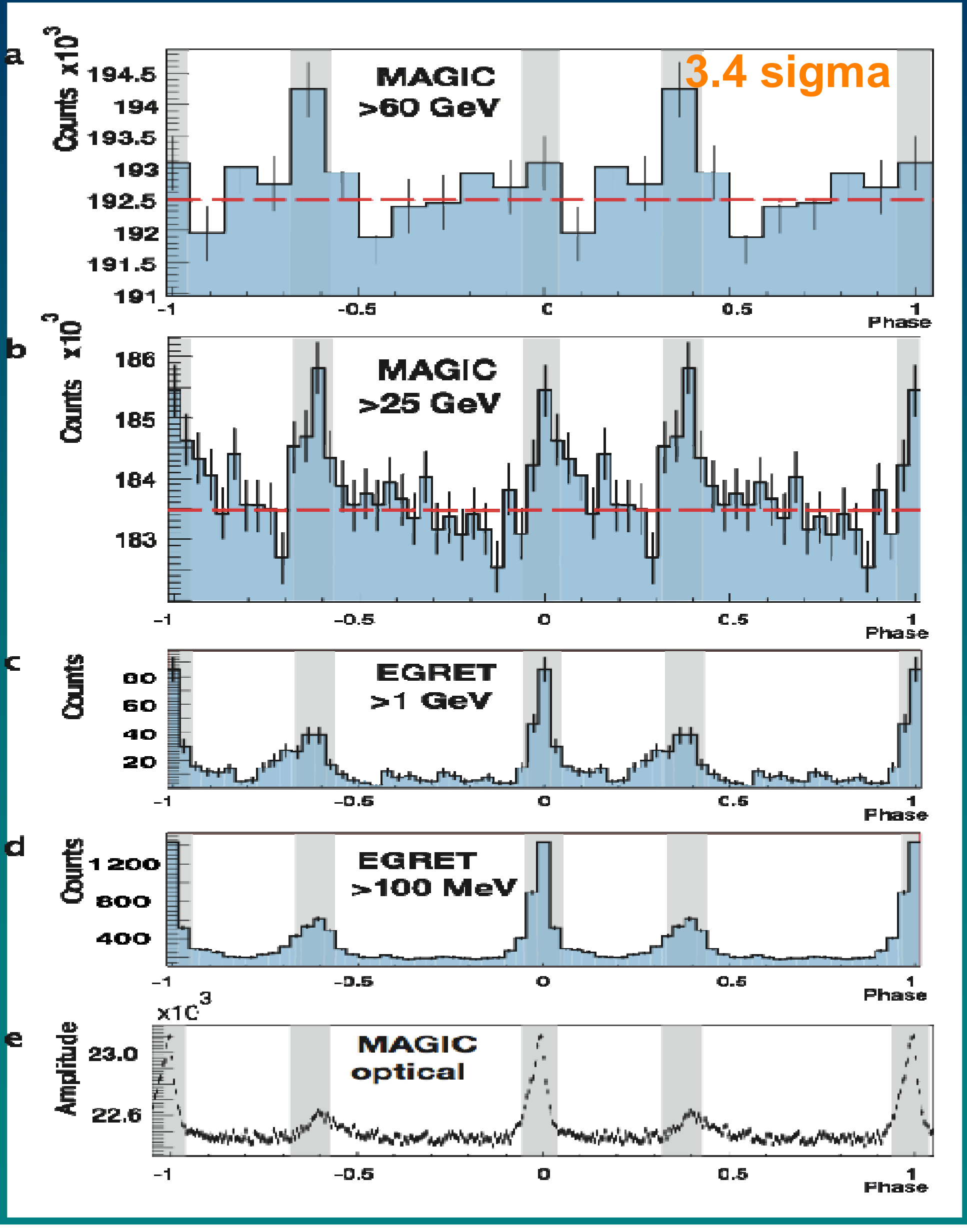
- Oct.07 to Feb.08: 22.3 h

Clear detection: 6.4 σ

Pulses in phase with EGRET

P1 clearly visible at 25 GeV
→*First Surprise*

Pulsed emission still visible > 60 GeV !
P2 became dominant



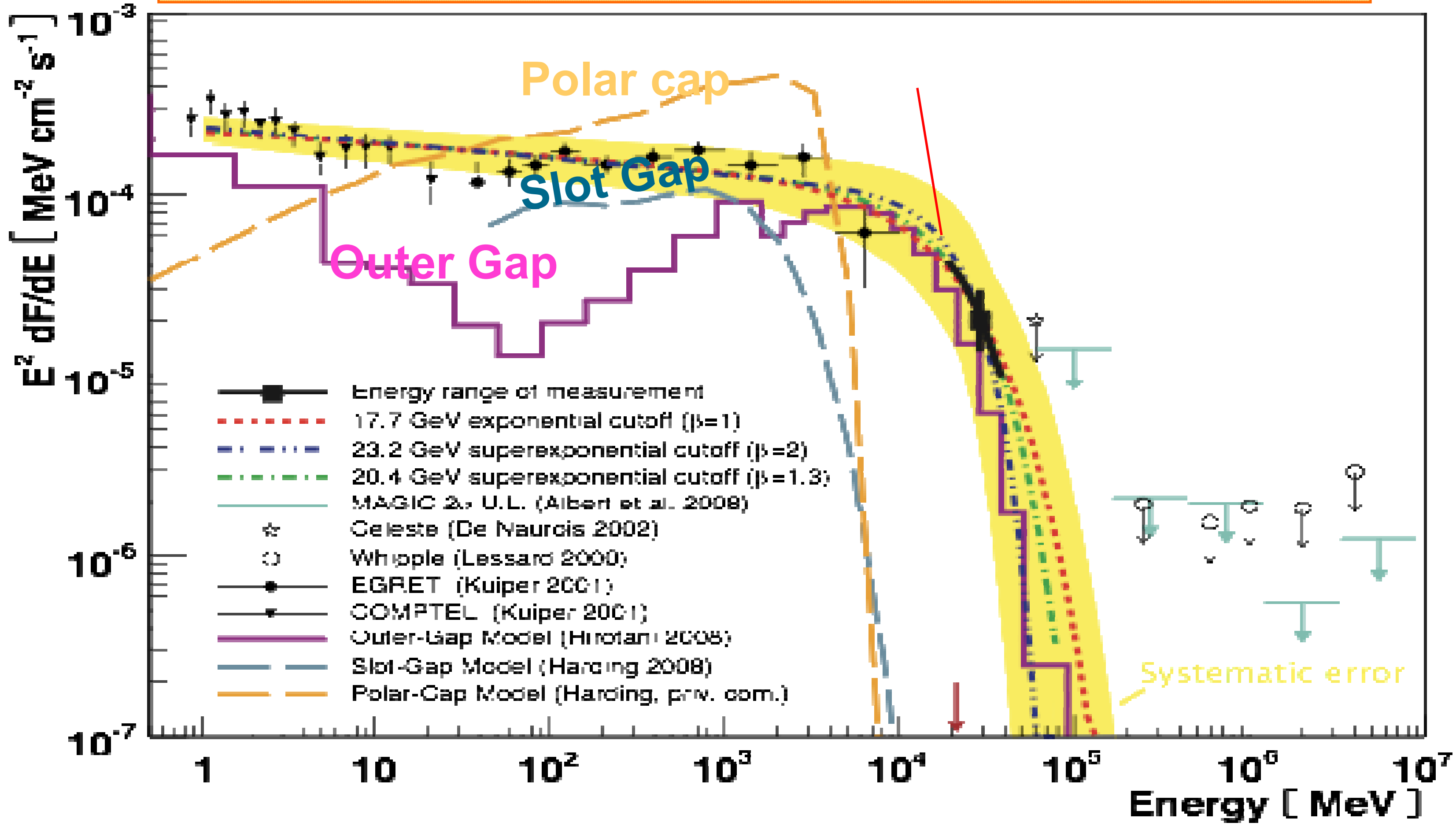
Pulsars

Total spectrum & cutoff

MAGIC

E0=17.7 ± 2.8$_{stat}$ ± 5.0$_{syst}$ GeV for β =1 (exponential)

E0=23.2 ± 2.9$_{stat}$ ± 6.6$_{syst}$ GeV for β =2 (super-exponential)



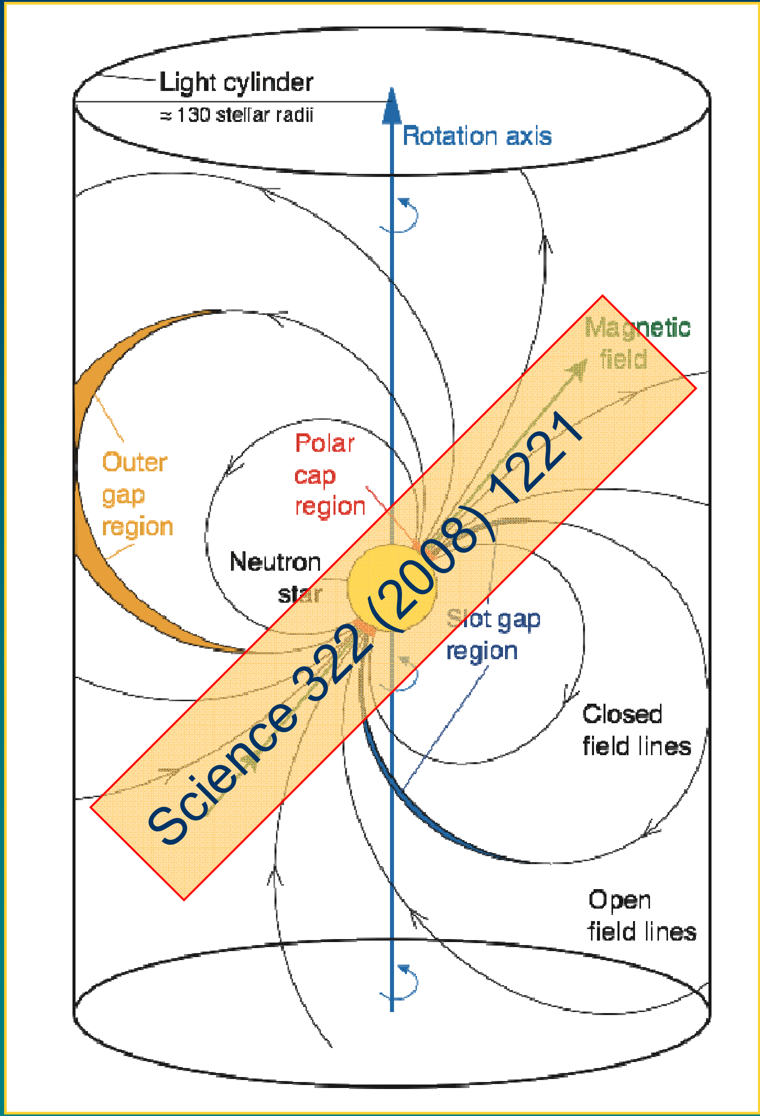
Relatively high cutoff >20 GeV !
Comparison with pulsar models

- Our superexponential cutoff:
  23.2 GeV+-2.9$_{stat}$ GeV+-6.6$_{syst}$ GeV
- We can calculate the absorption of gamma-rays in the magnetic field

$$\varepsilon_{\max} \approx 0.4\sqrt{P\frac{r}{R_0}}\max\left\{1,\frac{0.1B_{crit}}{B_0}\left(\frac{r}{R_0}\right)^3\right\}GeV$$

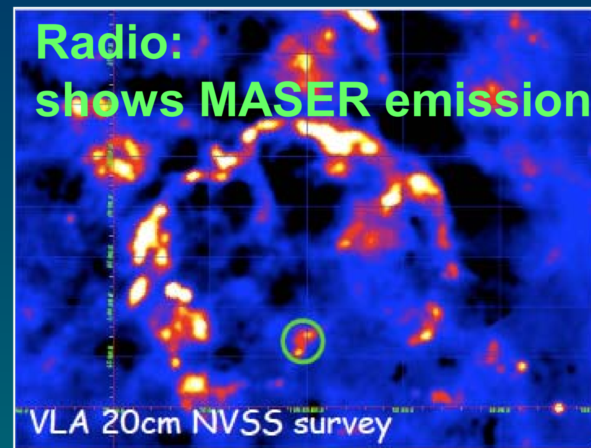
Baring et al., 2001

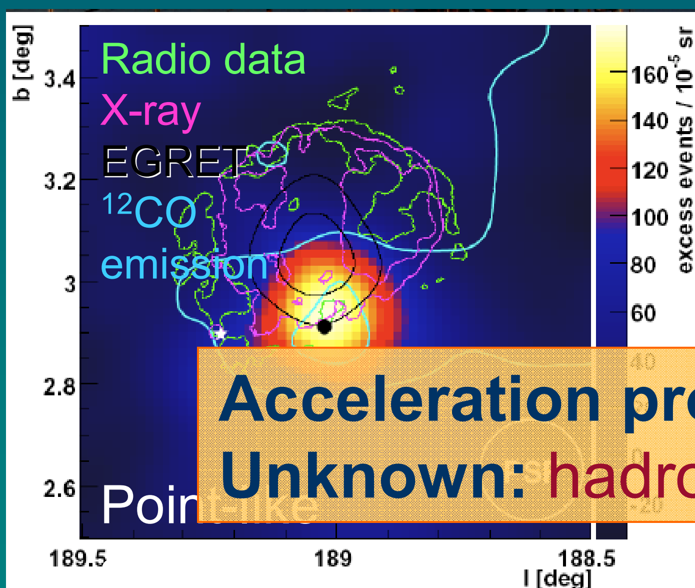
- From which we can put a lower limit on the distance of the emitting region:
  6.2 +- 0.2$_{stat}$ +- 0.4$_{syst}$ neutron star radii
- **The high location of the emission region excludes the *classical* polar cap model (emission distance < 1 stellar radius) and challenges the slot gap model**

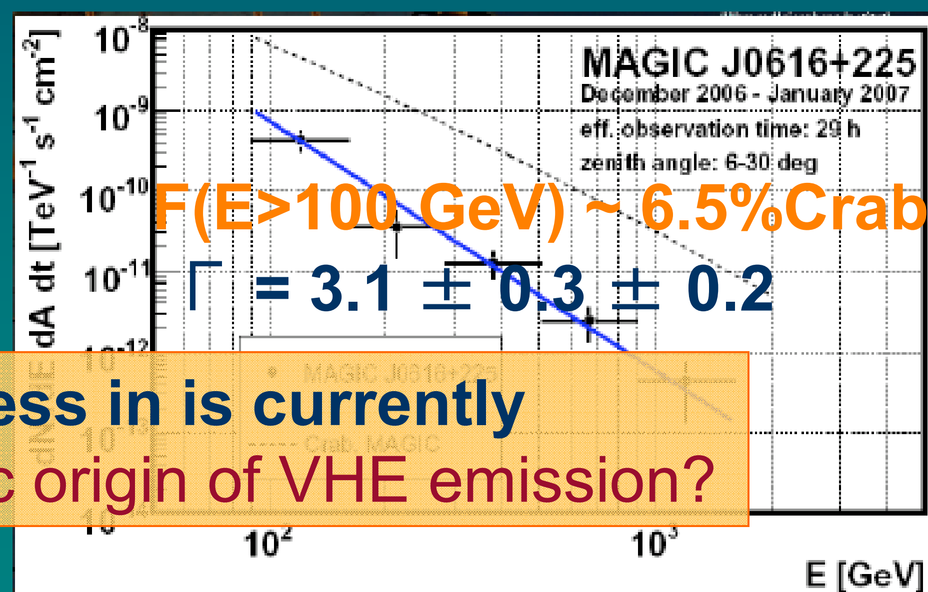


SNR IC 443 (MAGIC J0616+225)

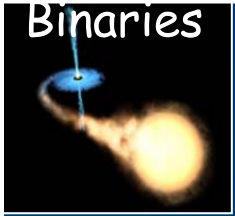
- Asymmetric shell-type SNR, 45' diameter (distance ~1.5 kpc)
  - Unidentified EGRET source inside
  - Only upper limits in VHE γ-rays
- Discovered by MAGIC in 2007
  (recently confirmed by Veritas)







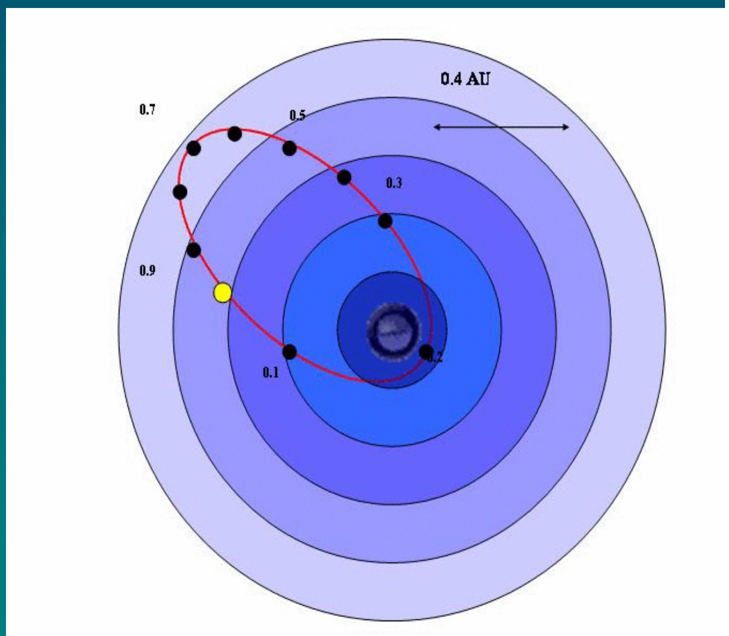
Acceleration process in is currently Unknown: hadronic origin of VHE emission?

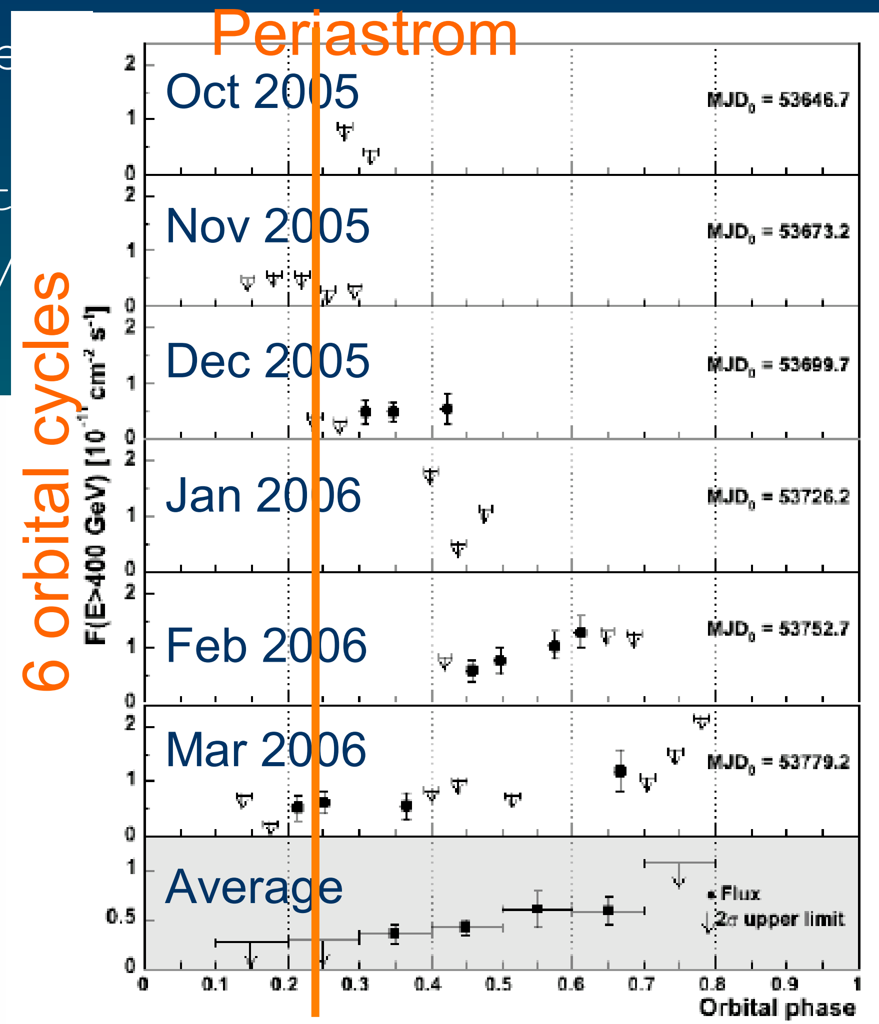


LSI+61 303

MAGIC

- High mass x-ray binary syste
  - Be start (18 $M_{\odot}$) &
  - Unknown compact object: neut
- Discovered by MAGIC in 2005/
- Visible only at some orbital phases

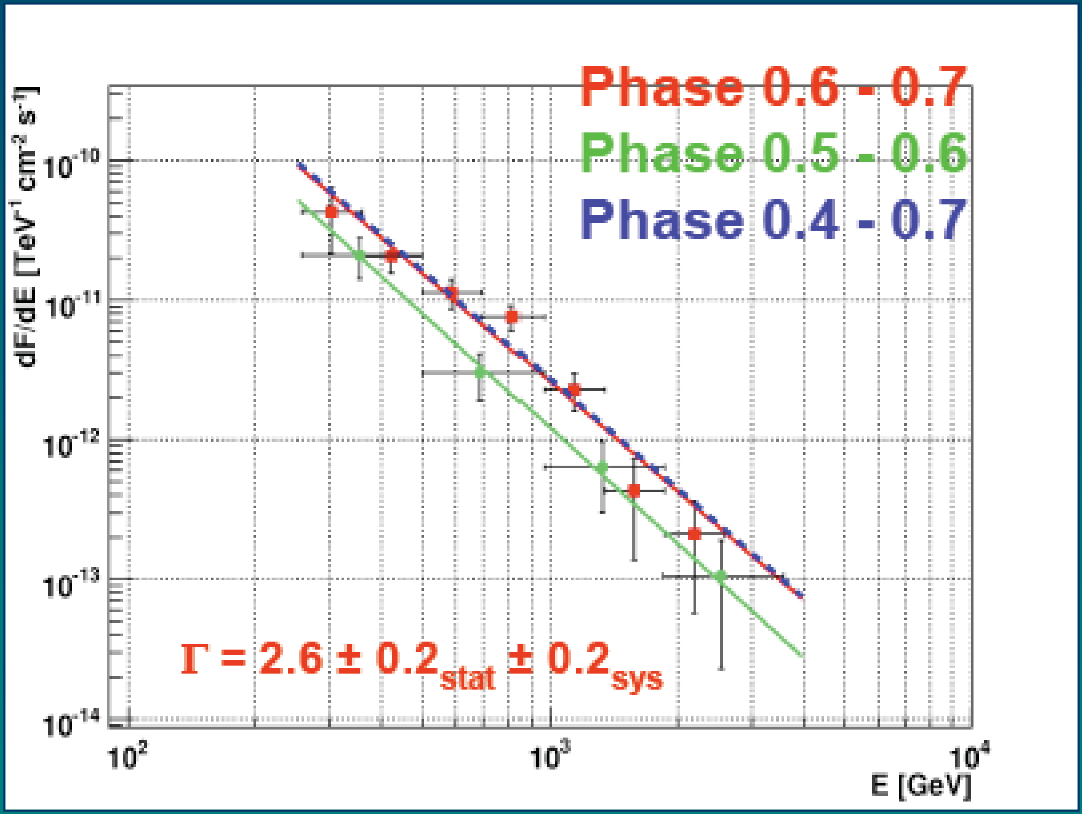




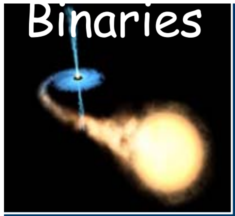
First time a periodically variable VHE emitter was seen

LSI+61 303: Spectrum

Spectral index remains during different phases, even if flux changes by factor of 3



Albert et al. 2009

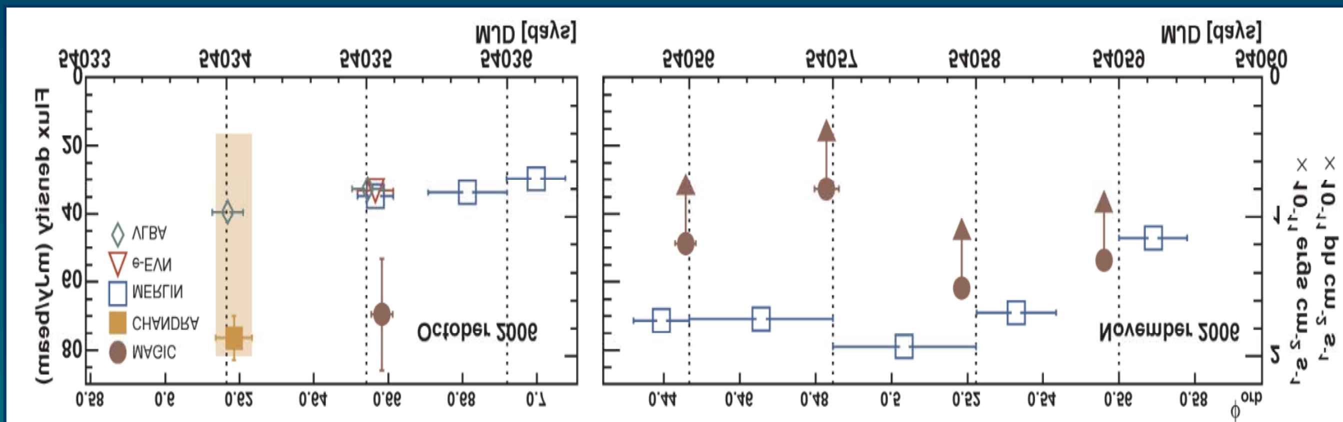


LSI+63 303: MW campaigns

MAGIC

Radio/VHE?

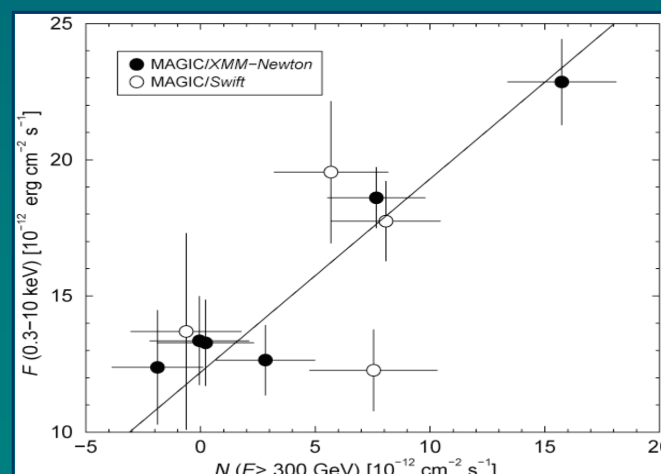
- MW campaign Oct/Nov 06 in Radio, X-rays & VHE



No direct correlation between radio/VHE

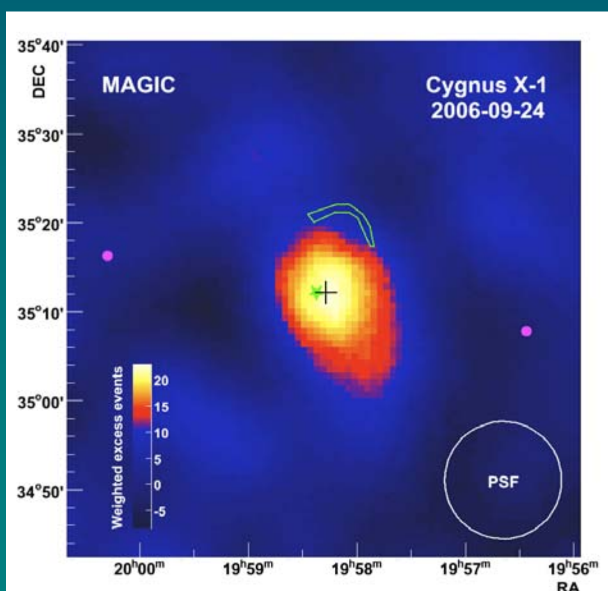
X-ray/VHE?

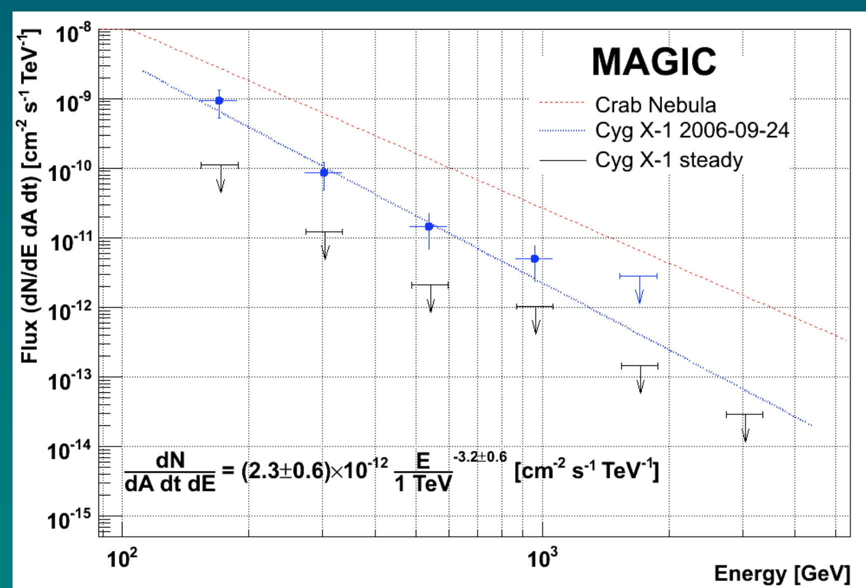
- New MW campaign in 2007 with XMM, Newton and Swift
  - Simultaneous data show evidence for X-ray/VHE correlation (r=0.81)



Cygnus X-1

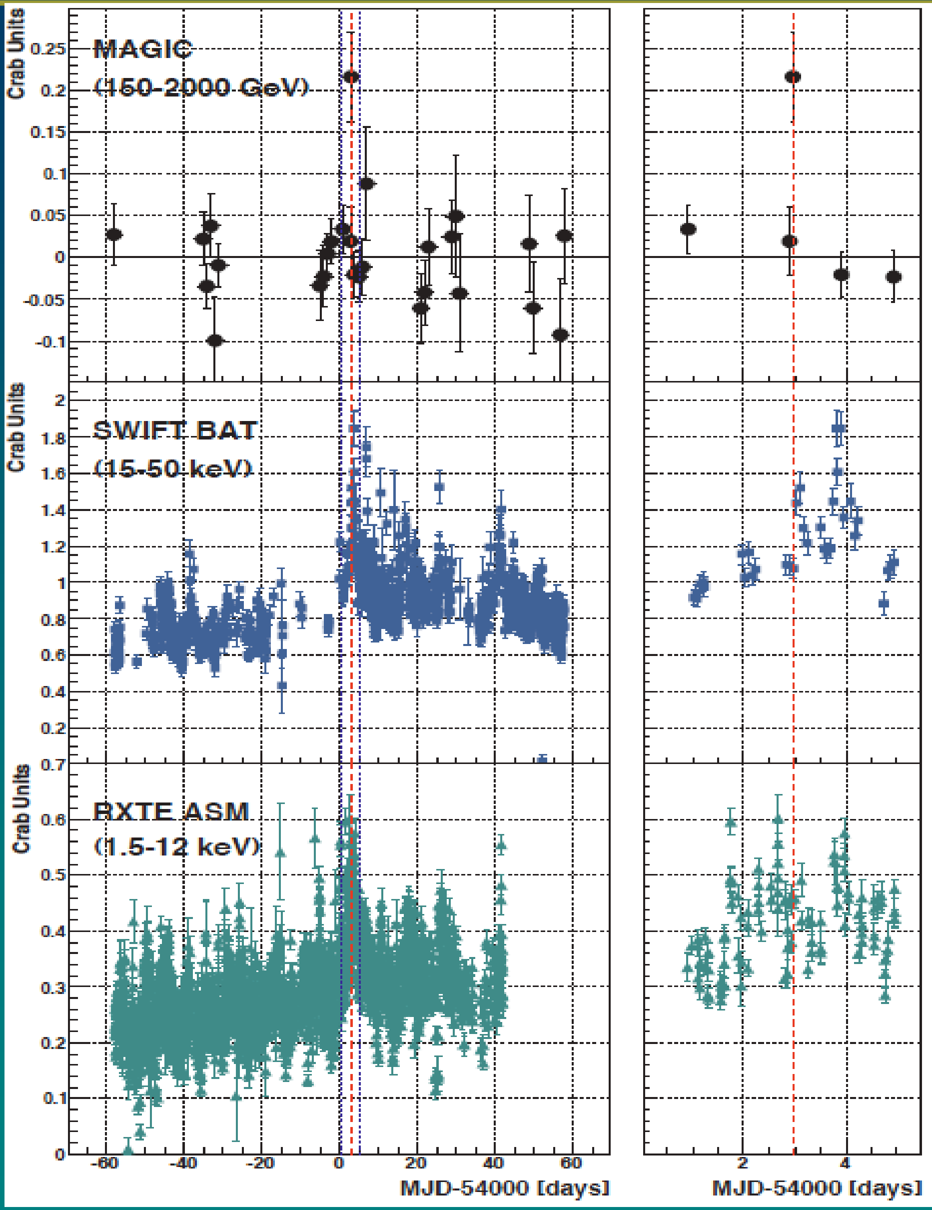
- One of the brightest X-ray sources in the sky
  - BH turning around an O-type star
- Observed 40h in 2006 with MAGIC in 26 nights
  - No steady γ-ray signal: U.L. below ~1% Crab flux
  - Detected a flare on 24th Sept. 2006 at 4.1 σ (post trial)

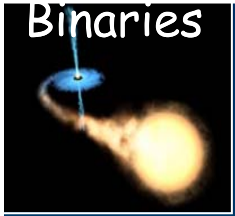




Cygnus X-1

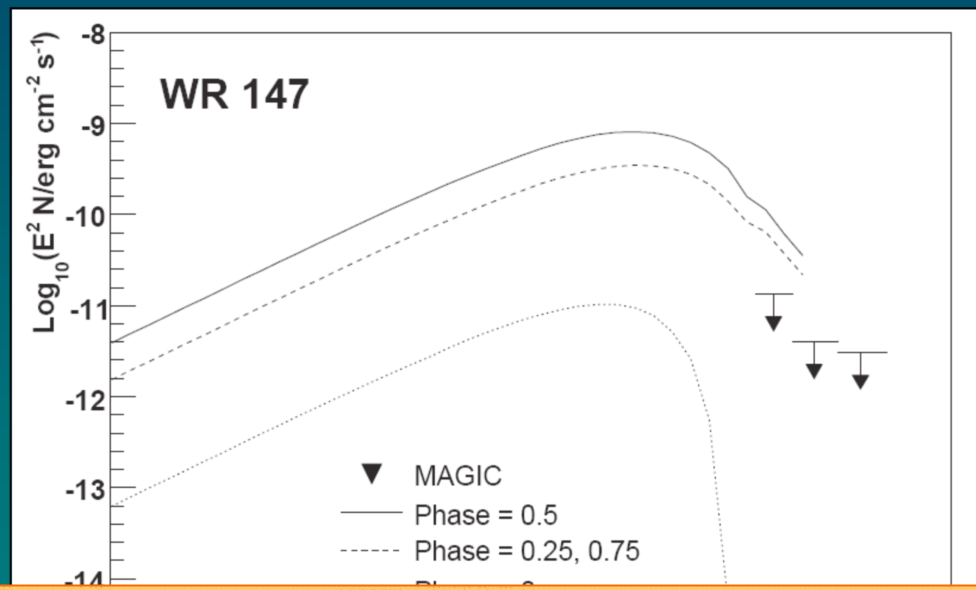
- VHE flare coincident with X-ray flares seen by Swift/BAT, RXTE/ASM and Integral
- TeV excess observed at rising edge of first hard X-ray peak
- Hard X-rays and VHE γ-rays could be produced at different regions of the jet → shift between TeV- and X-ray peak





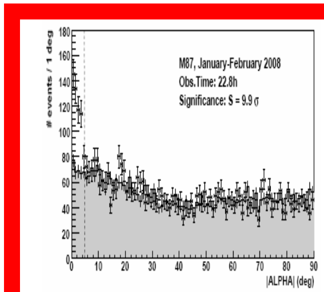
Wolf-Rayet binary systems

- Binary systems containing a WR star :
  - colliding winds (up to 5000km/s) could produce γ-rays via leptonic or hadronic processes (e.g. Reimer et al. 2006)
- MAGIC observed two WR binary systems:
  - **WR146:** WC6+O8 colliding wind binary system in the field of view of TeV J2032+4130; combined observation, T=30h
  - **WR147:** WN8(h) plus a

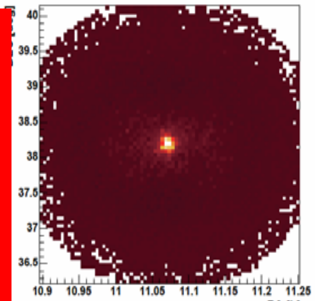


Reimer's model for WR147 assumes parameters still unknown ➔Model can't be rule out, but the phase can be constrained (period is 1500yrs!)

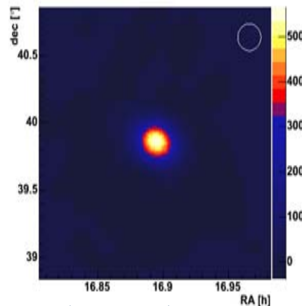
Highlights in MAGIC extragalactic observations



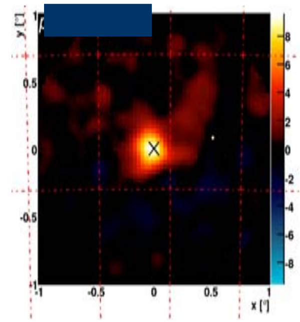
M87 (z=0.0043)



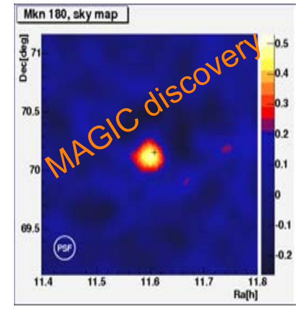
Mrk421 (z=0.031)



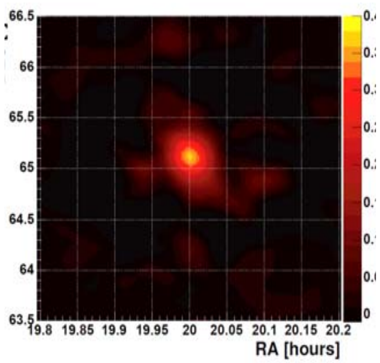
Mrk501 (z=0.034)



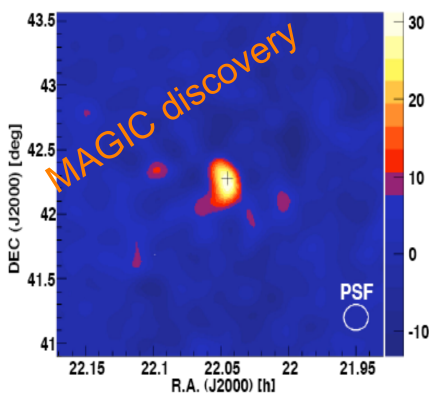
1ES2344 (z=0.044)



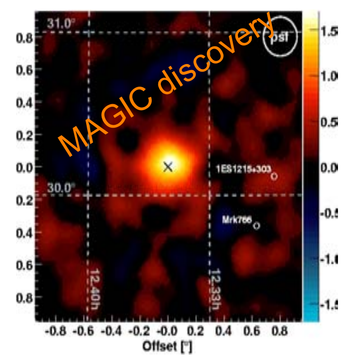
Mrk180 (z=0.045)



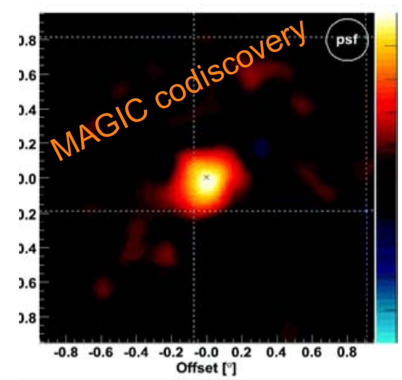
1ES1959 (z=0.047)



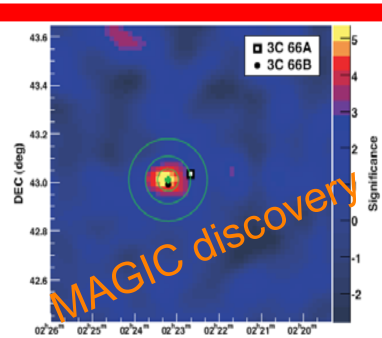
BL-Lacertae (z=0.069)



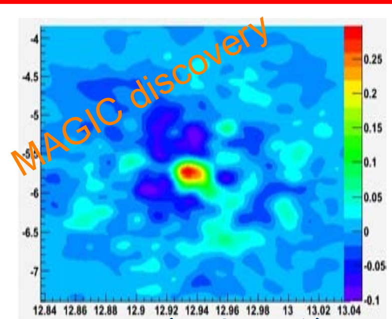
1ES1218 (z=0.18)



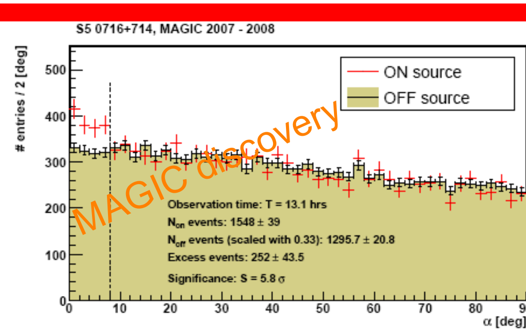
PG 1553+113 (z>0.25)



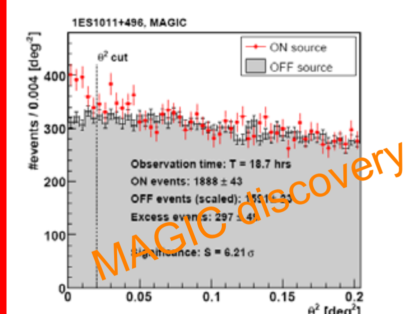
MAGIC J0223 (3C66B?)



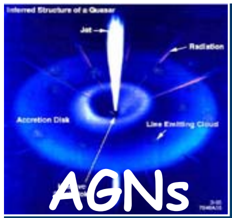
3C279 (z=0.536)



S5 0716 (z=0.31)

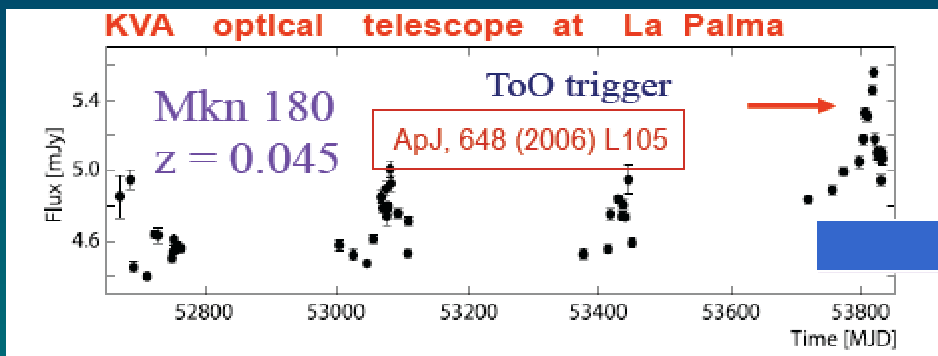


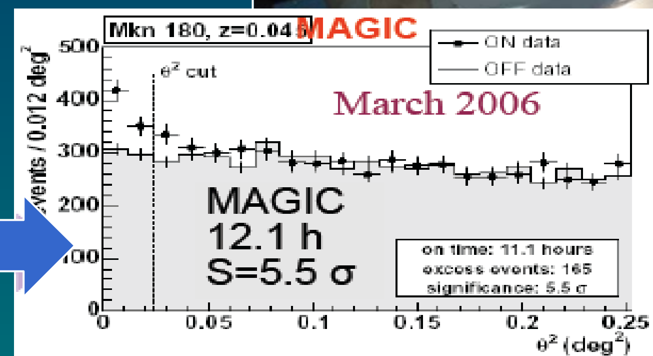
1ES1011 (z=0.212)

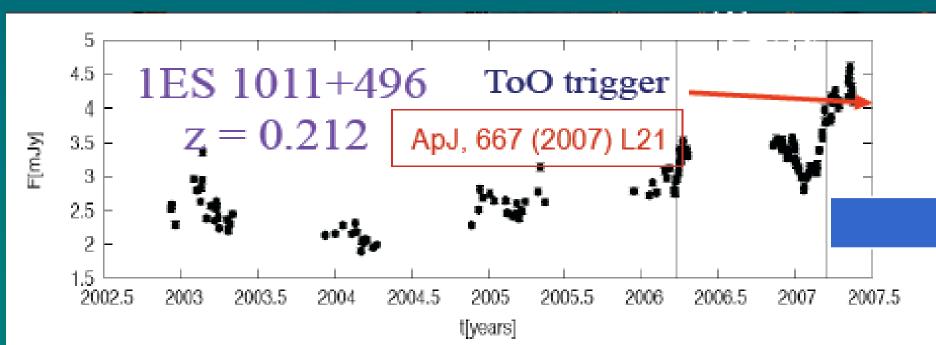


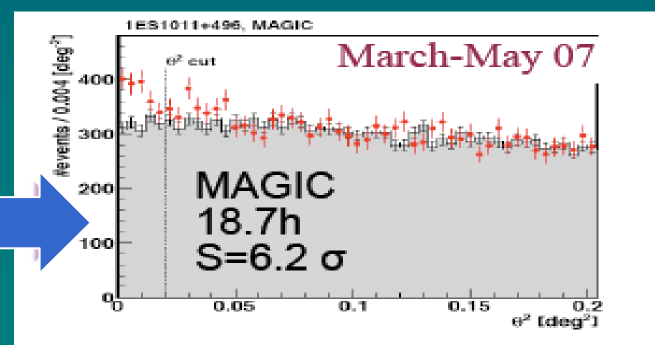
Optical triggers→new VHE sources

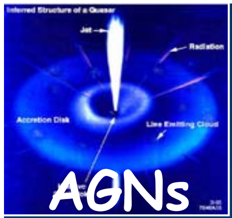
- Regular optical monitoring of candidate sources by KVA telescope (close to MAGIC site)





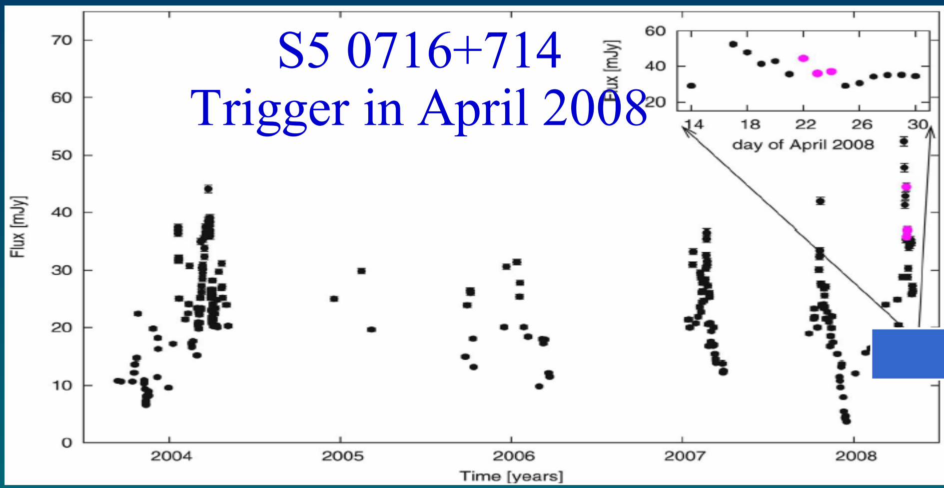


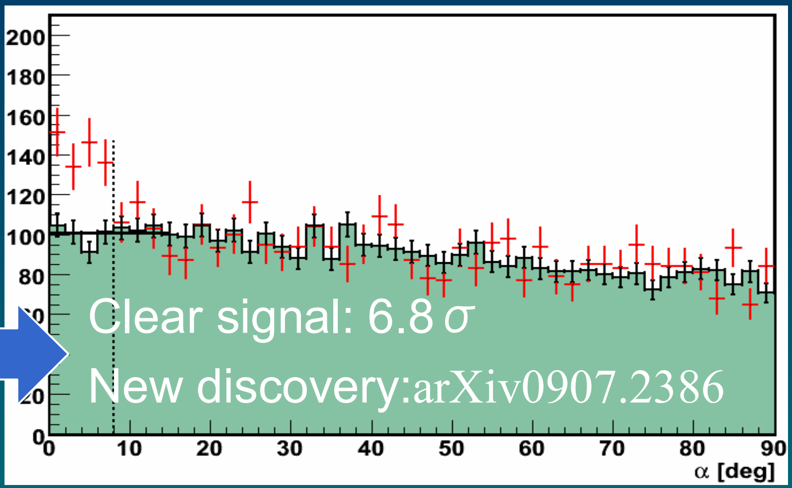




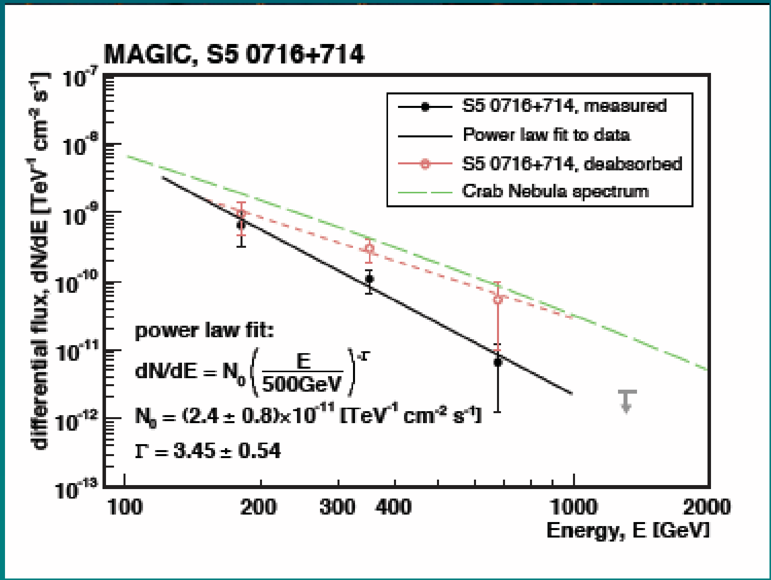
MAGIC

S5 0716+714



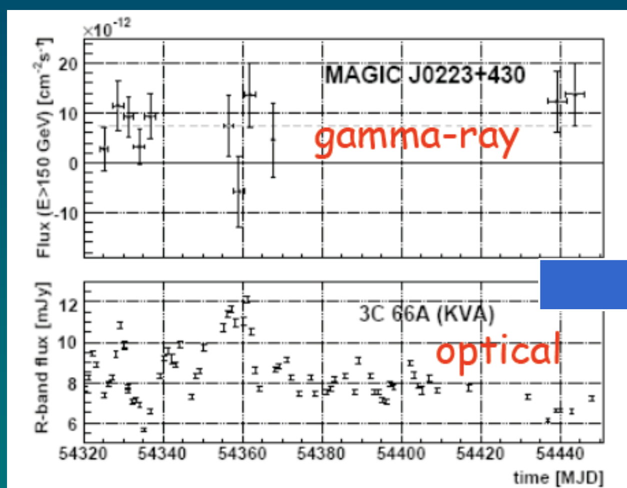


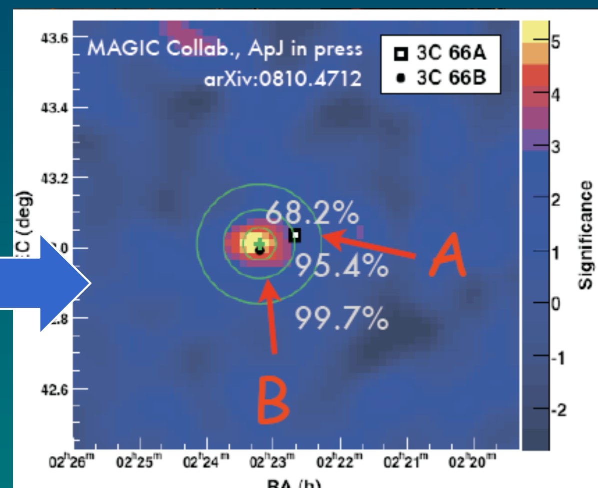
- After trigger, MAGIC observed 2.6h
  - April 28: Swift reports flux about 50% larger than that observed in 2007
  - Apr 29: ATel #1500, MAGIC reports 6.8 σ discovery Apr 23-25. F(>400 GeV) ≈25% Crab
- 3rd low-peaked VHE blazar after BL Lac & W comae
- Host galaxy detected: Z=0.31+/-0.08 2nd farthest VHE emitter



Observations in the vicinity of 3C 66A

- Optical outburst in August 2007 triggered MAGIC observation:
  - from August to December, a total of 54.2 h
- Detection at 5.4 σ , F(E>150 GeV) = 2.2% Crab



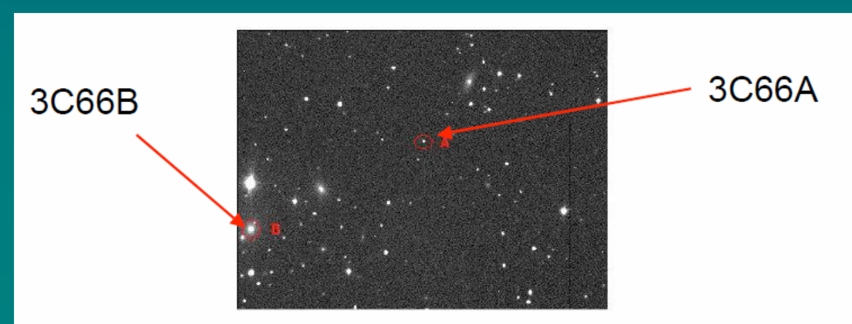


3C 66B is the most likely identification:

3C 66A excluded with 85% probability

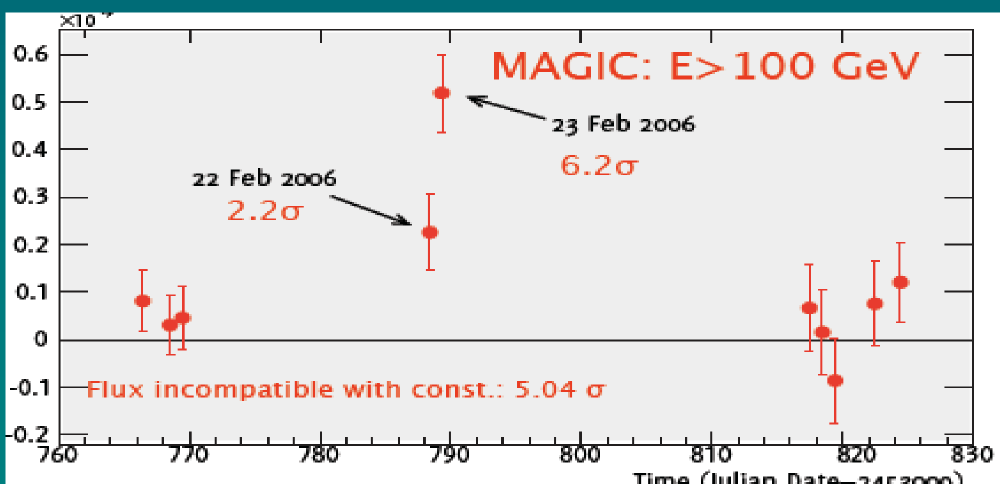
A or B?

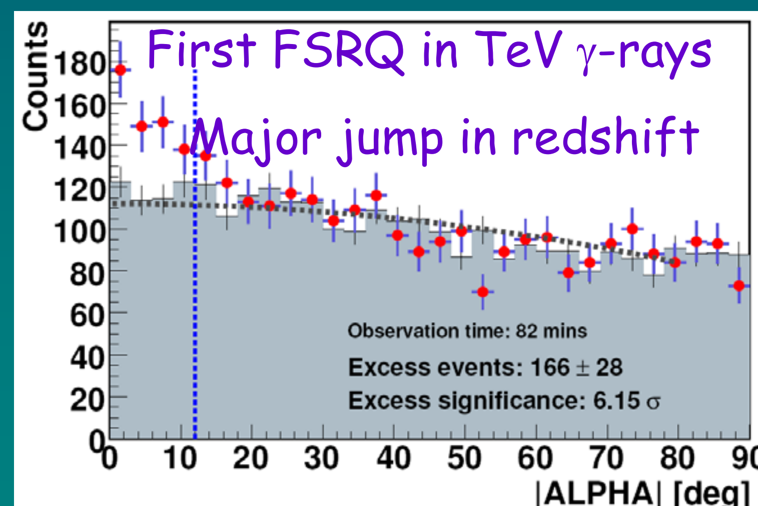
- **3C 66A/B: just separated 6' in the sky**
  - 3C 66A blazar with uncertain redshift, z=0.32-0.44
  - 3C 66B large FR-I radio galaxy, similar to M87, z=0.0215



The distant quasar 3C 279

- Flat spectrum radio quasar (z=0.54)
- Very bright and strongly variable
  - Brightest EGRET AGN
  - Gamma-ray flares in 1991 and 1996. Fast time variation (~ 6hr in 1996 flare)
- MAGIC observations
  - 10 h between Jan.-April 2006
  - clear detection on 23[rd] Feb. at 6.2 σ

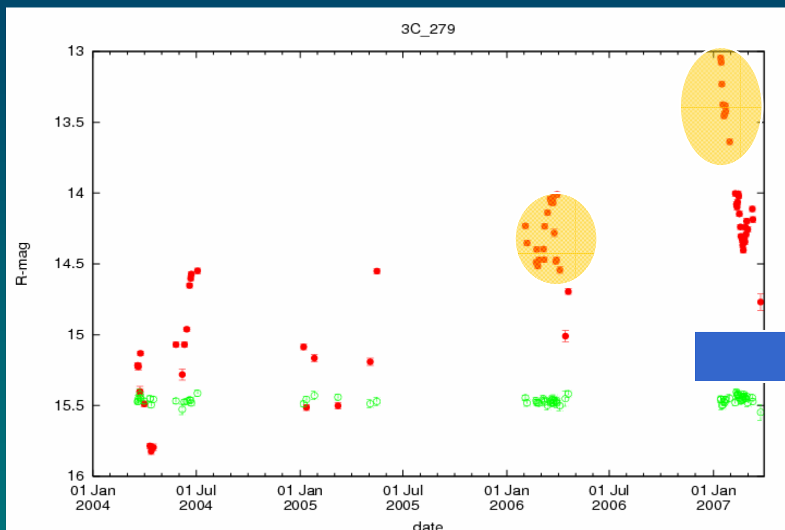


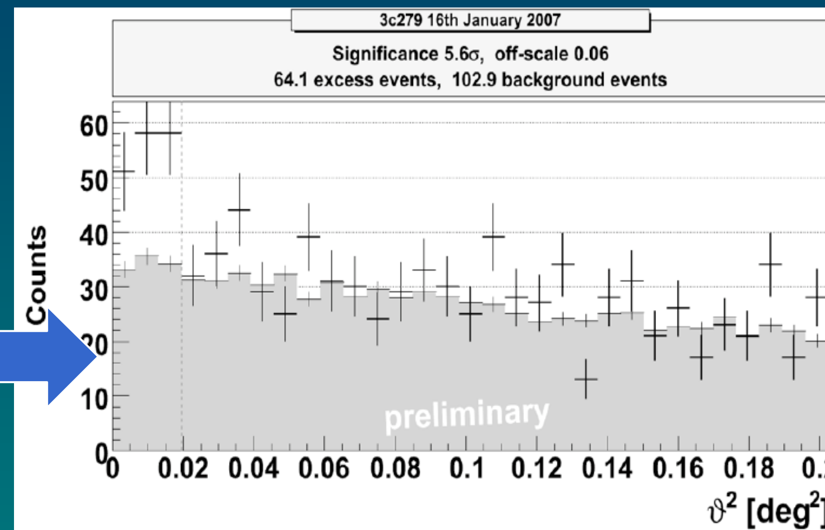


The distant quasar 3C 279

- New observations after optical outburst in Jan. 2007

  → New flare detected

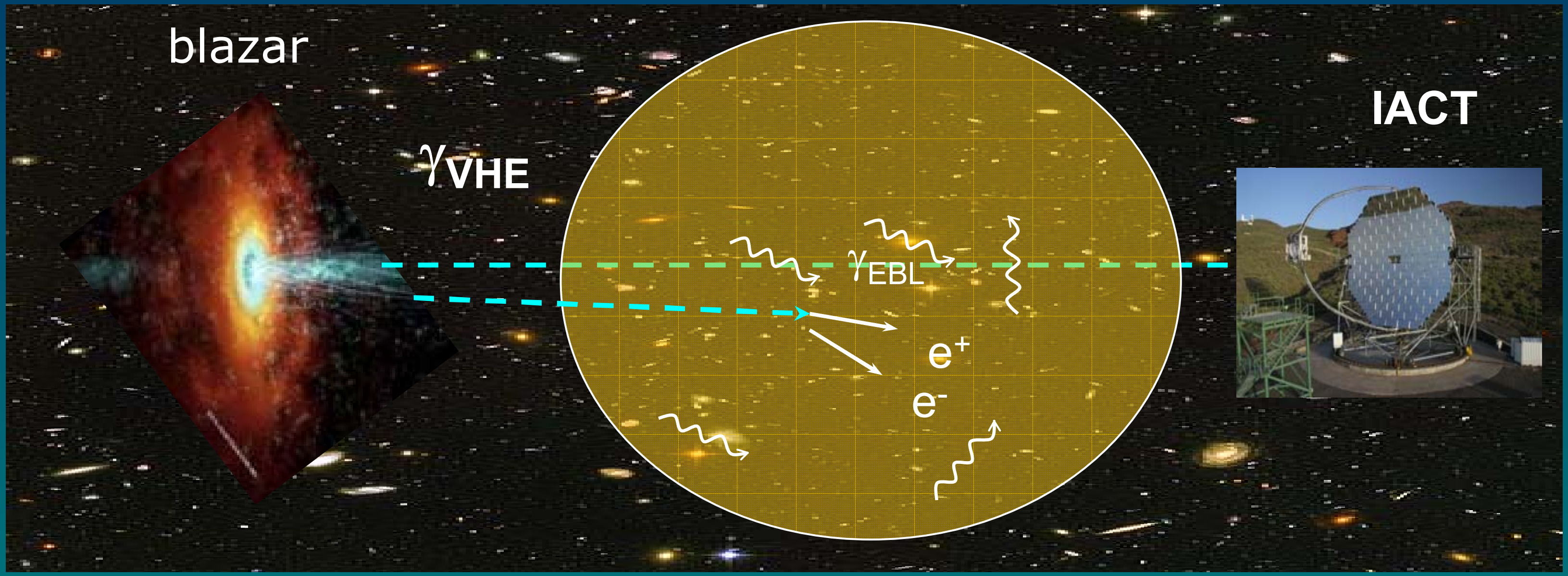




Most distant object ever detected at VH,E during two flares
(Feb. 2006 and Jan. 2007)

Emission harder than expected -> constrains the EBL, universe more transparent to Υ-rays than expected

Implications on Extragalactic Background Light



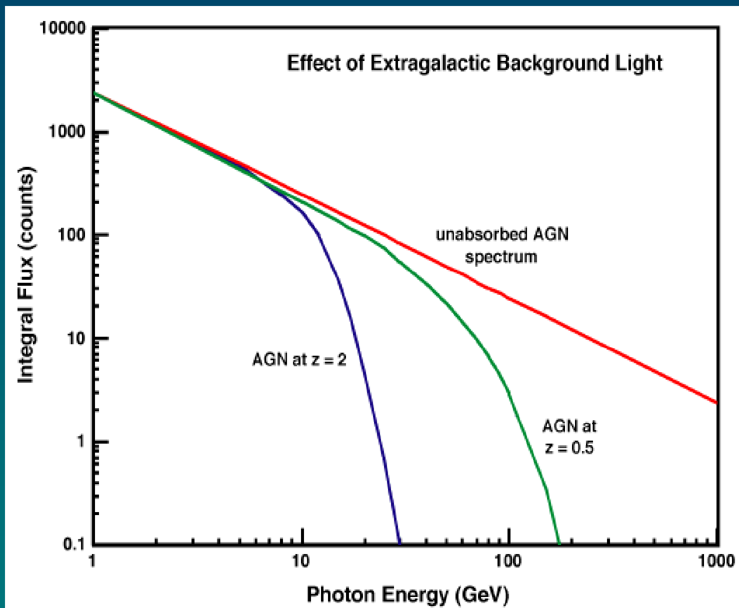
- γ-rays from the source interact with the EBL in their way to the Earth, protuding e+/- pair.
- For γ-rays, relevant background component is optical/infrared (EBL)
- different models for EBL: minimum density given by cosmology/star formation

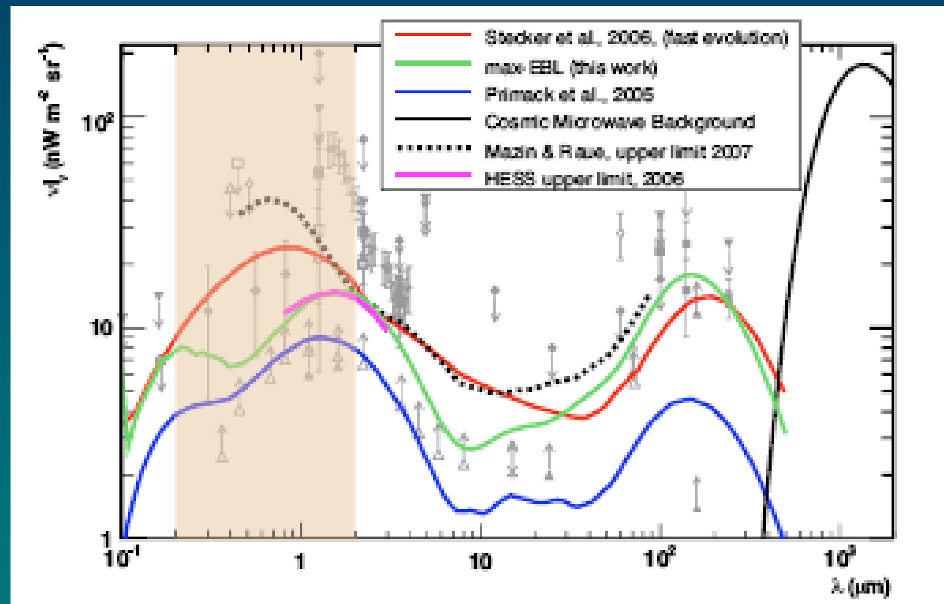
Implications on Extragalactic Background Light

MAGIC

AGNs & EBL

- Measured spectrum affected by attenuation in the EBL



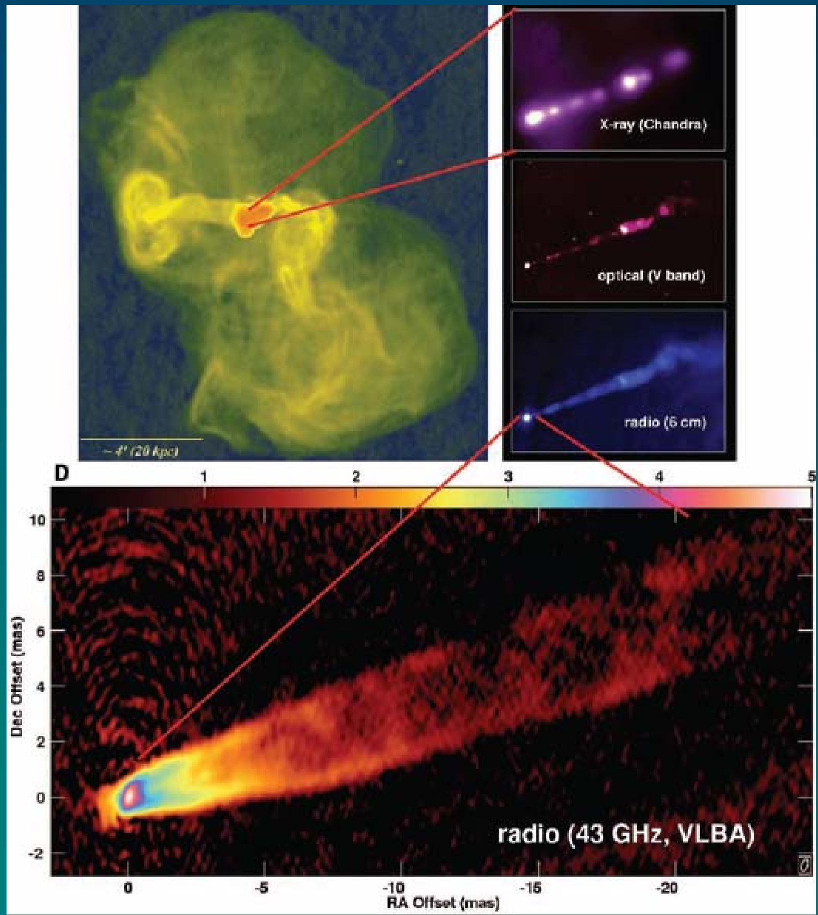


- Measurement of spectral features permits to constrain EBL models:
  - 3c 279 Power law Γ =- 4.11+/-0.68 ➔Spectrum sensitive to 0.2 to 2 μm
  - Assume minimum reasonable index α = 1.5:
    - Upper limit close to lower limit from galaxy count

The Universe appears more transparent at cosmological distances than believed

M87 giant flare

- Radio galaxy with super massive black hole ~ $6 \cdot 10^9 M_\odot$ at ~ 16Mpc
- Jet structure with knots, sometimes brighter than nucleus
- Established VHE Υ-ray emitter: HEGRA, HESS, Veritas & MAGIC
  - Site for TeV emission (core/HST-1)?
- Source of UHECR?



M87 giant flare

Science, 325 (2009) 444

Joint paper MAGIC-VERITAS-HESS-VLBI-Chandra

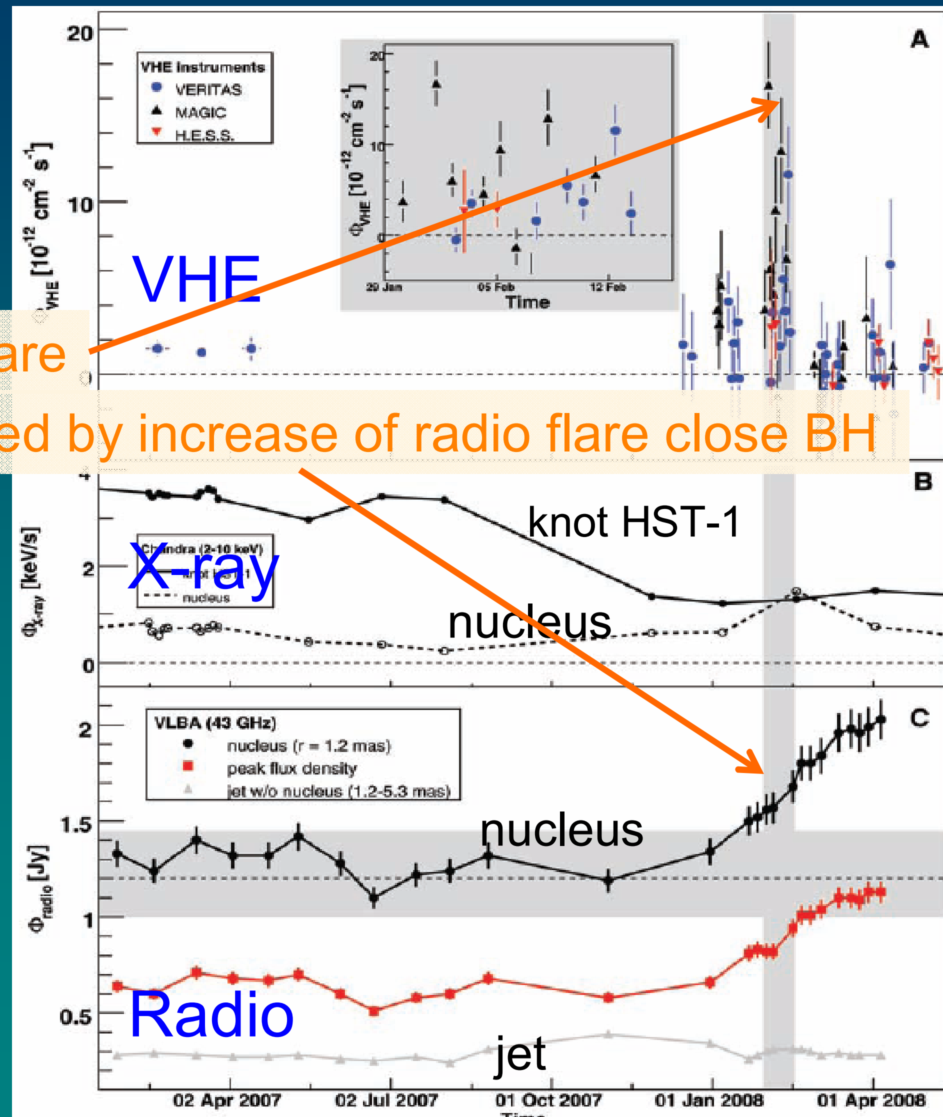
MAGIC

MWL campaign Jan-Feb 2008

- Triggered by MAGIC detection on 1st February flare:
  - 9.9σ detection; 8.0σ sing
  - night 1st-feb
- Discovered:
  - Fast (day-scale) variability
  - Correlated TeV flare with radio & X-ray emission from the core, while emission from HST-1 knot stayed low
- Origin of the VHE Υ-ray emission is most likely the core of the jet

VHE flare

Followed by increase of radio flare close BH



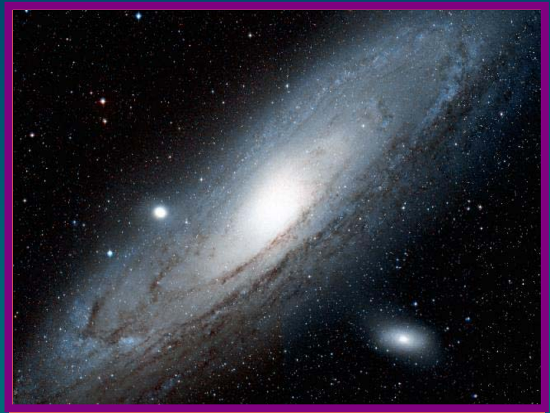
Indirect Dark Matter searches

- Standard Cosmological scenario of Cold Dark Matter
- Neutralino (lightest SUSY particle) attractive candidate

γ-flux from χ annihilations:

$$\Phi_\gamma(\Omega) \propto \boxed{\frac{N_\gamma v\sigma}{M_\chi^2}} \boxed{\int \rho_{DM}{}^2(l)dl(\Omega)}$$

Particle phys. X Astrophysics



CDM density: γ-ray flux ~ ρ^2 => need region with high ρ

Where to search?

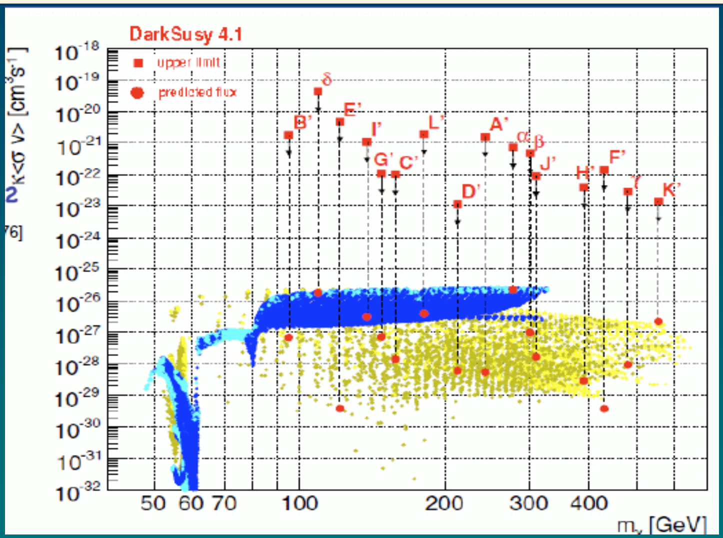
- Galactic center? obscured by strong VHE source
- Other galaxies, galaxy clusters? expect other VHE
- minihalos, IMBHs, ...? don't know where they are (yet)
- spheroidal satellite dwarf galaxies ? expect to be dim but cleaner signal

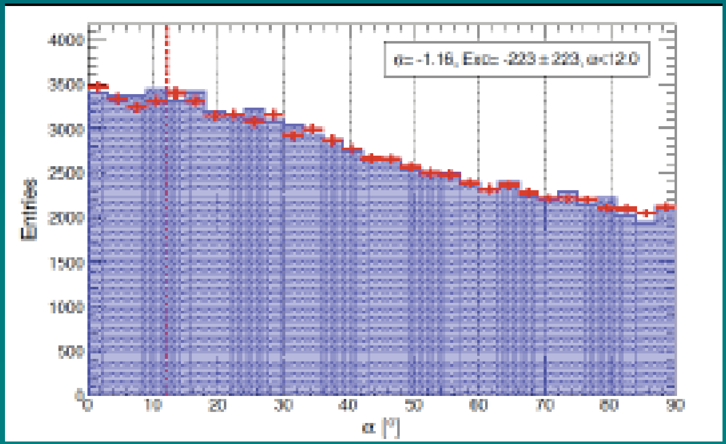
Observations of Sph. dwarf galaxies

MAGIC

Need significant increase in sensitivity to come close to model predictions

- Draco
  - 8h in 2007 at large zenith angle (37^{o}) =>E_{th}=140GeV
  - u.l.: Φ(E>140GeV)~$10^{-11}\,\gamma\,cm^{-2}s^{-1}$ (assuming spectral index -1.5)
  - U.l. depends on expected spectra: different for each mSUGRA model
- Willman I
  - 15h in 2008
  - u.l.: Φ(E>100GeV)~$10^{-11}\,\gamma\,cm^{-2}s^{-1}$





MAGIC goes stereo…

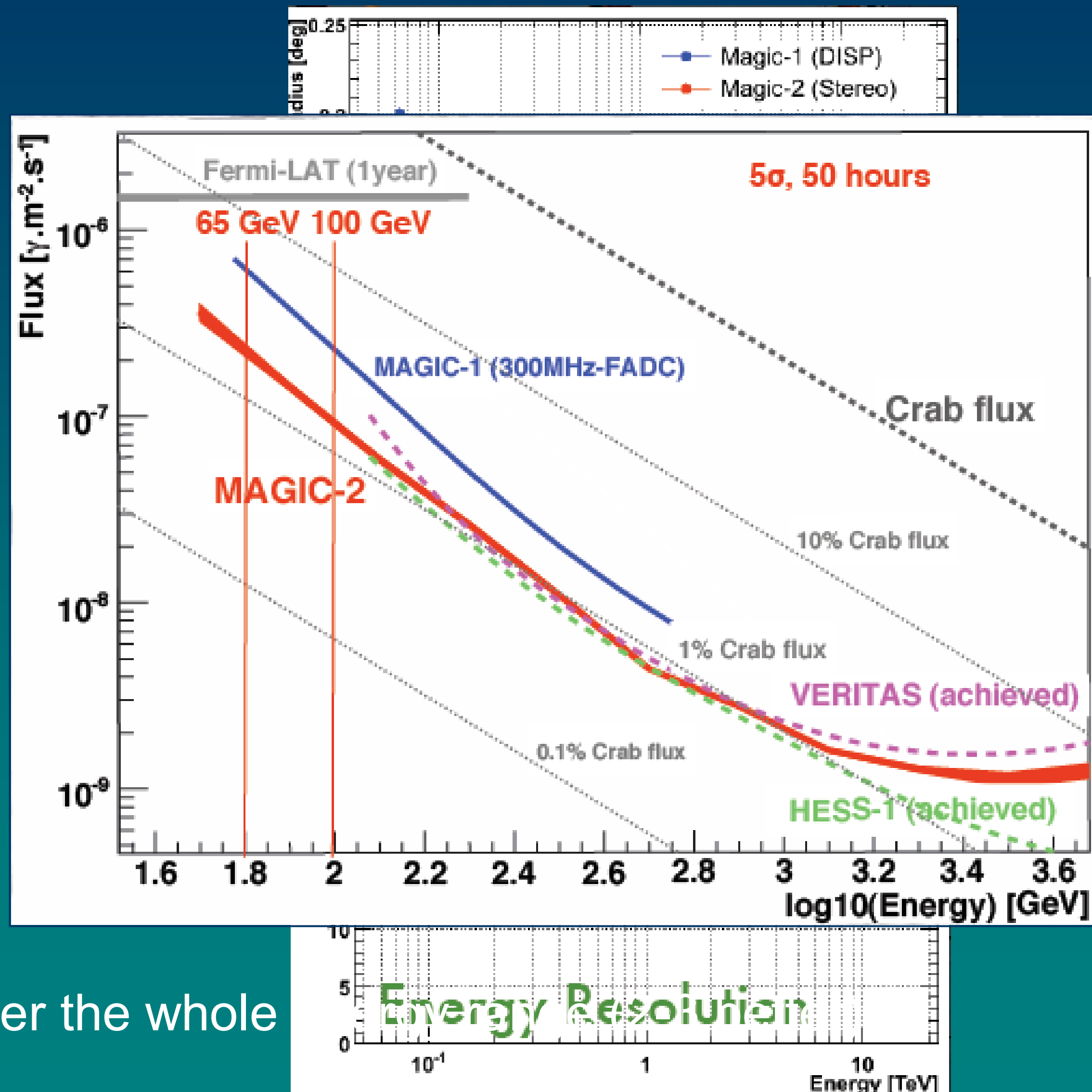
Why stereo?

Stereoscopic provides:

- Better reconstruction of shower direction
- Additional shower param.:
  - Impact parameter
  - Shower maximum
- Eliminate ambiguity on shower arrival direction

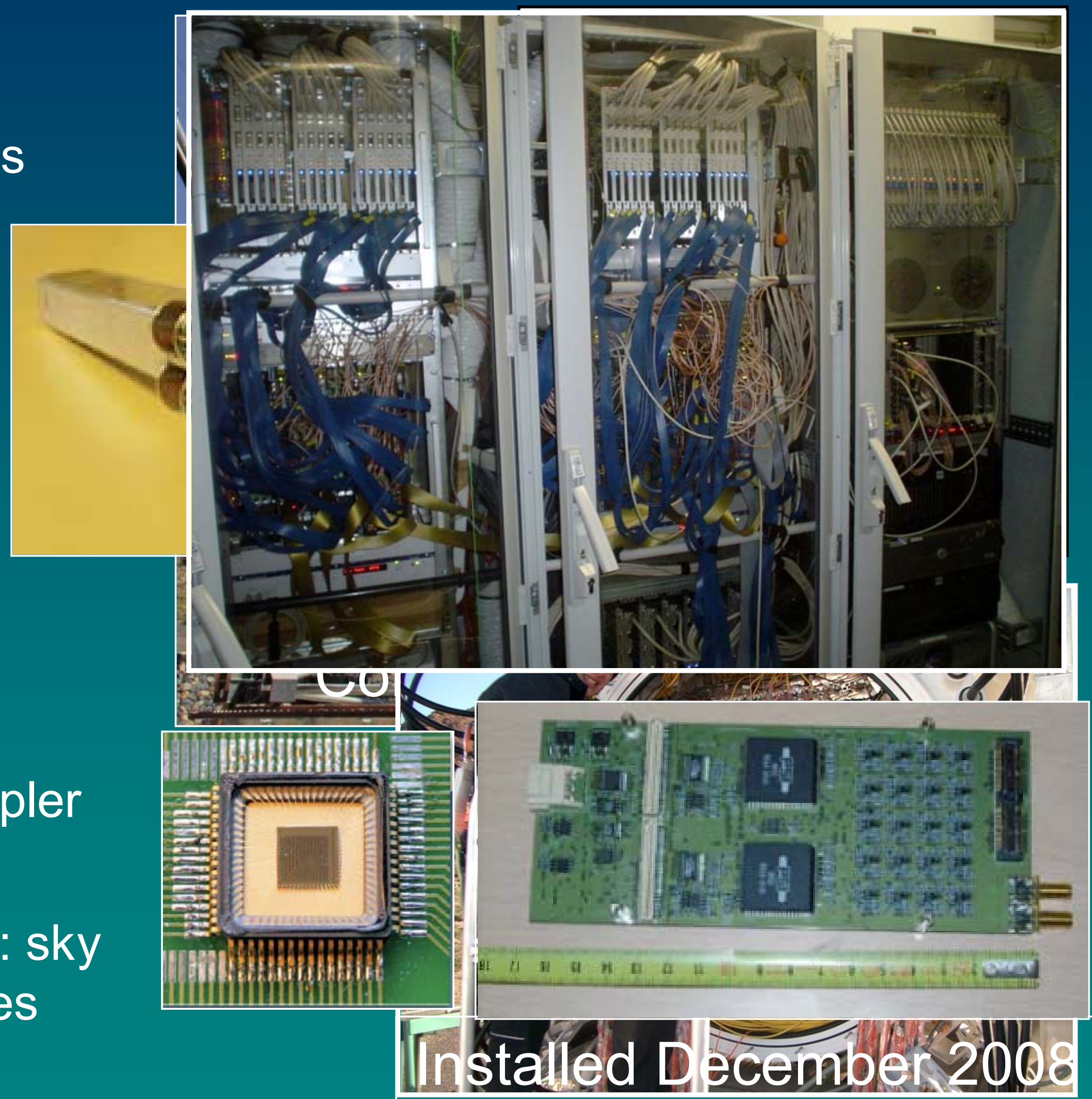
This means:

- Better hadron rejection
- Better angular resolution
- Better energy resolution
- Enhance the sensitivity over the whole



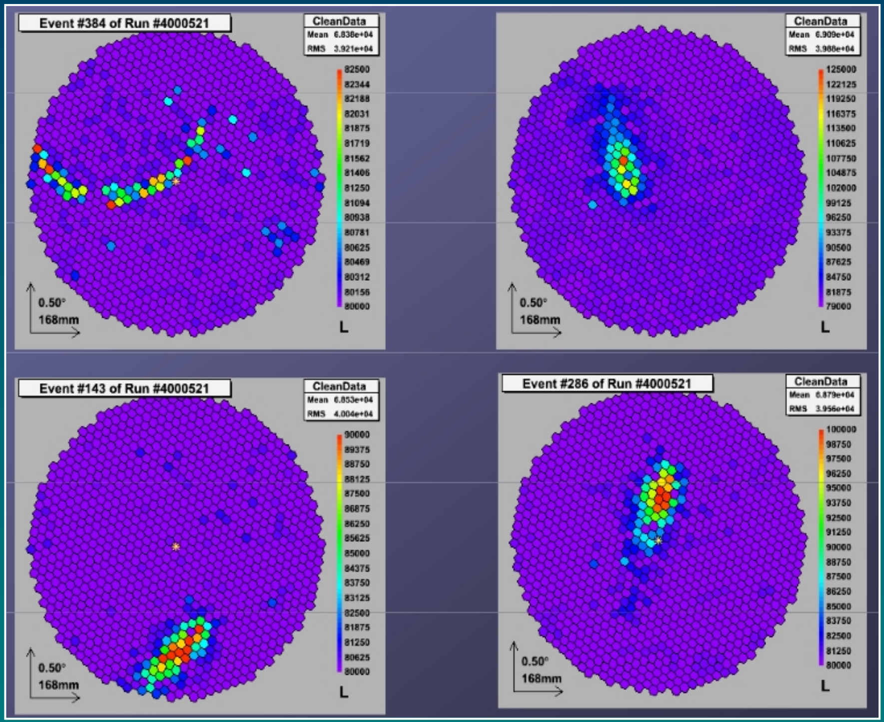
MAGIC-II not just a clone

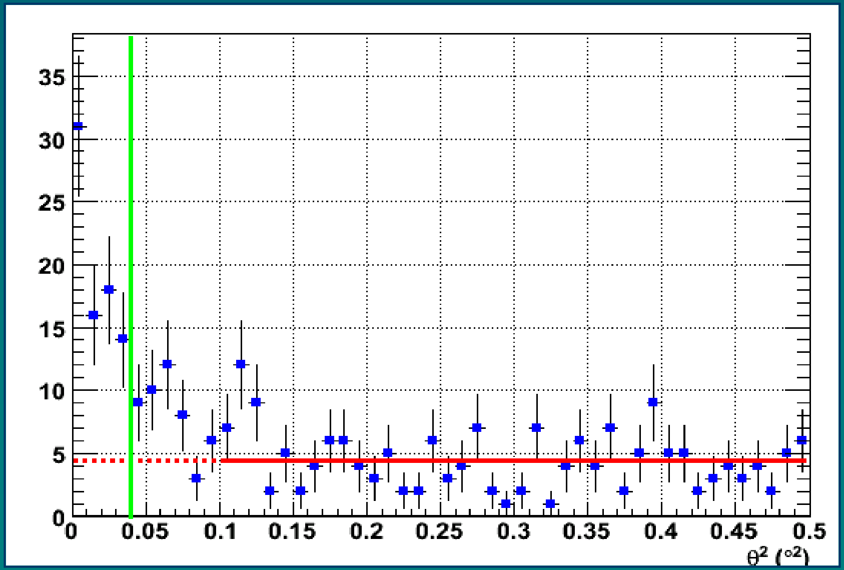
- Improved $1m^2$ mirrors:
  - bigger, lighter
  - 2 technologies: Al, glass
- Improved camera:
  - High efficiency PMTS
    - 1039 x 0.1^o pixels
  - Modular Design
    - Cluster of 7 pixels
    - Easy replacement
  - Total FOV = 3.5^o
- Improved readout:
  - Uses DominoRing sampler
- Increased trigger area
  - Improved sensitivity for: sky scans, extended sources



MAGIC-II already running!

- First images & inauguration in April 2009
- First stereo events in June
- Since September all data taken with both telescopes





Conclusions

- MAGIC is producing high quality physics after 4 observation cycles:
  - last year 15 articles published, 2 in Science
- We have discovered new sources (and new populations)
  - 4 new galactic sources + 8 extragalactic, and studied many others in high detail
- Important contributions to the understanding of pulsars, AGN, EBL…
- MAGIC-II just started regular operations

"The story of the MAGIC project is a textbook example of the merging of particle physics and astronomy into the modern field of astroparticle physics"

BACKUP

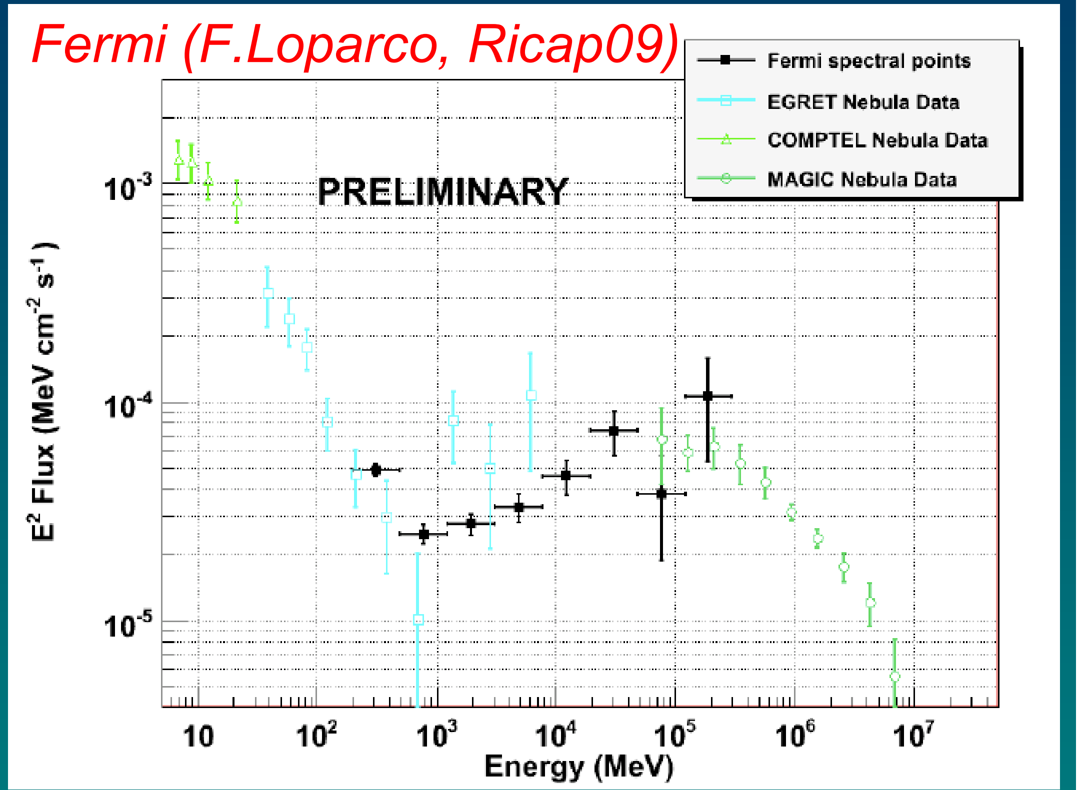
Best studied: the Crab Nebula

MAGIC

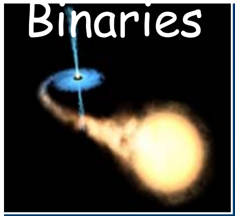
- Crab Nebula spectrum measured with high precision between 60GeV and 9TeV
  - Good agreement with other other CTs above 400 GeV
- First determination of the IC-peak:

  E = (77 ± 35) GeV

- Spectrum well described within SSC model



<u>The GeV – TeV connection</u>:
The Crab Nebula can be used as cross-calibration source
→ reduce uncertainty in the energy scale of IACTs



LSI+63 303: Is the LC periodic?

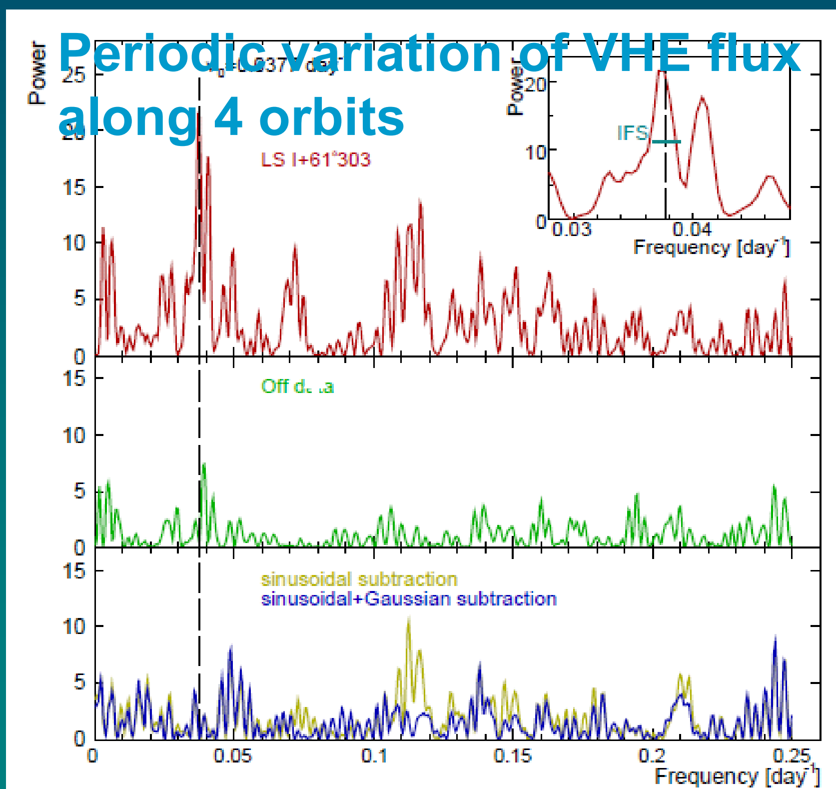
MAGIC

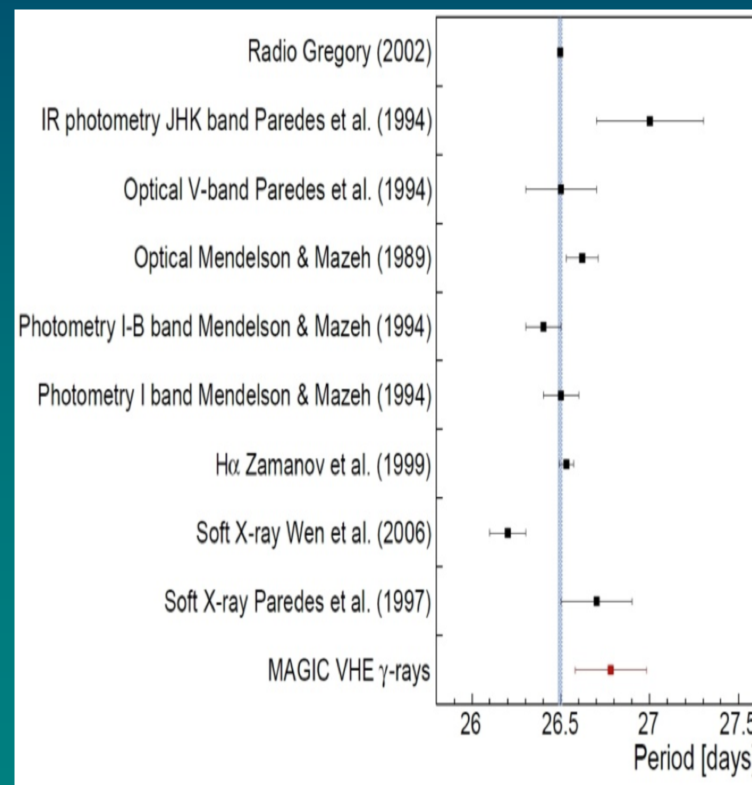
- Periodicity test reveals highly significant period

  P = 26.8±0.2 days

  – consistent with emission at other wavelengths

Periodic variation of VHE flux along 4 orbits



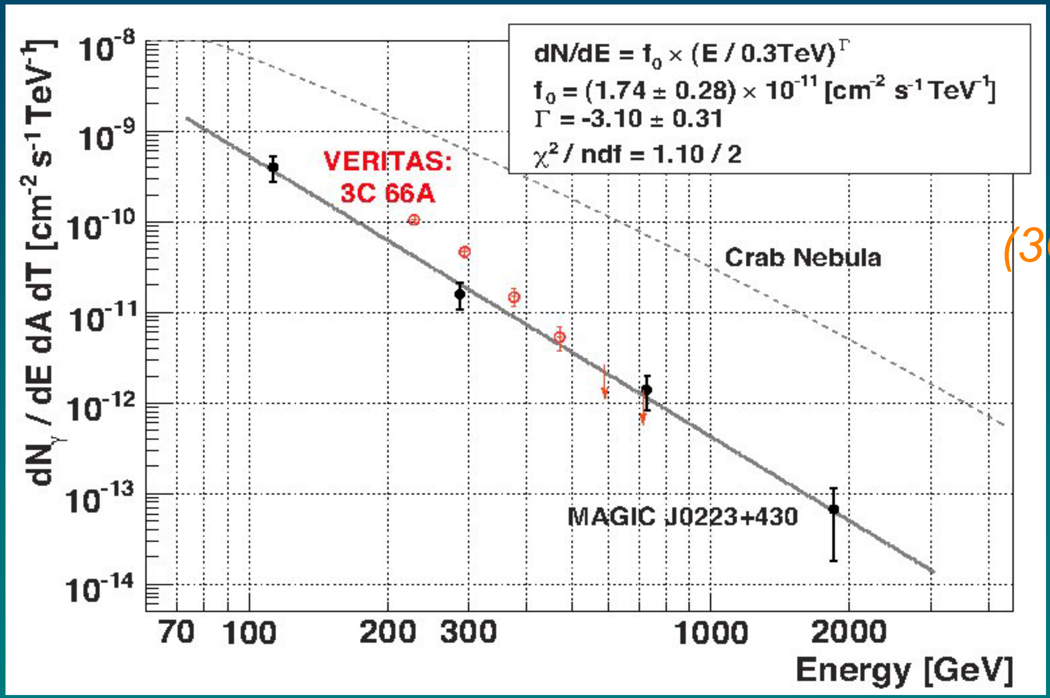


Albert et al. 2009

Observations in the vicinity of 3C 66A

MAGIC

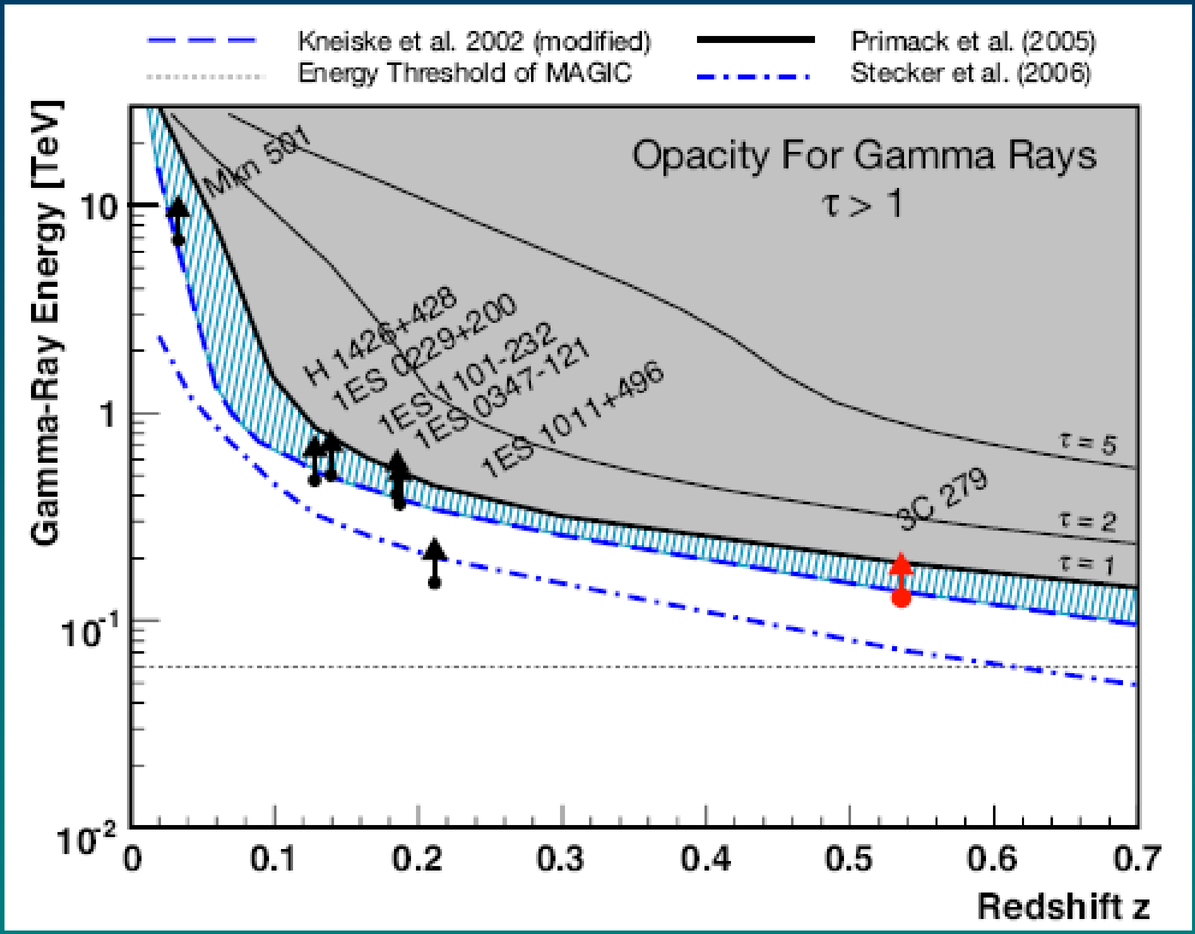
F(E >150 GeV) ~ 2.2% Crab ➔ lowest ever detected by MAGIC
(Cannot exclude contribution of 3C 66A at lowest energies)



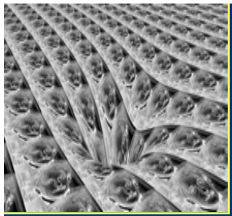
VERITAS spectrum (3C66A) index: 4.1+-0.4+-0.6

If 3C66A (unlikely) ➙ distance cannot be z > 0.23 (no > 1 TeV γ-rays, EBL)
Hard spectra possible, but require unusual blazar energetics ($L > 10^{47}$ erg s^{-1}!)

3C279 and the γ-ray horizon



Test of the transparency of the universe extended to z = 0.536!



Fundamental physics

MAGIC

Energy-delayed flare of Mrk501

- Quantification of the delay:

  $\Delta t = 0.030 \pm 0.012$ s/GeV

  Probability of no delay: 2.6%

- Possible explanations:
  - Astrophysical: intrinsic source effects

    IF

  - photons at different energies were emitted simultaneously:

    Propagation effect due to Lorentz invariance violation:

$$c' = c\left[1 \pm \xi \frac{E}{E_s} \pm \zeta \left(\frac{E}{E_s}\right)^2\right] \qquad \Delta t \approx \frac{\Delta E}{E_S}\frac{L}{c}$$

➔Probing the Planck energy scale